NASA CONTRACTOR REPORT 166539

Static Feed Water Electrolysis Subsystem Testing and Component Development - Final Report

(NASA-CR-166539) STATIC FEED WATER ELECTROLYSIS SUBSYSTEM TESTING AND COMPONENT DEVELOPMENT Final Report (Life Systems, Inc., Cleveland, Ohio.) 91 p HC A05/MF A01 CSCL 06K G3/54
N84-17856
Unclas
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CONTRACT NAS2-11087
September, 1983

NASA

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Prepared for
Ames Research Center
under Contract NAS-2-11087

National Aeronautics and
Space Administration

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FOREWORD

The development work reported herein was conducted by Life Systems, Inc. at Cleveland, Ohio, under Contract NAS2-11087 during the period September 15, 1981 through September 14, 1983. The Program Manager was Franz H. Schubert. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Carl N. Baron	Software Design, Test Support
Ken A. Burke	Unitized Core/Composite Cell Development, Feedwater Electrolyte Elimination Studies
Steve Czernec	Mechanical System and Test Support Accessories Assembly
Robert W. Ellacott	Component Assembly
James H. Fort	Component Design, Packaging, Test Support Accessories Design and Fabrication
Tim M. Hallick	Subsystem Evaluation, Module Assembly
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Don W. Johnson	Electronic Assembly and Checkout
Eugene P. Koszenski	Supporting Technology Studies, Internal Management Activities, Final Report Preparation
Ray Klimas	Electronic Hardware Design
Franz H. Schubert	Program Management and Subsystem Design
Lowell E. Wolfe	Supporting Technology Studies, Fabrications and Evaluations
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LIST OF ACRONYMS

ADC	Analog to Digital Converter
CCA	Coolant Control Assembly
C/M I	Control Monitor Instrumentation
CRT	Cathode Ray Tube
DAS	Data Acquisition System
DARS	Data Acquisition and Reduction System
DMA	Direct Memory Access
EC/LSS	Environmental Control/Life Support System
FCA	Fluid Control Assembly
I/O	Input/Output
IRAD	Internal Research and Development
LRU	Line Replaceable Unit
LSI	Life Systems, Inc.
M/E A	Mechanical/Electrochemical Assembly
NASA	National Aeronautics and Space Administration
OGS	Oxygen Generation Subsystem
PFC	Power Failure Control
RTE	Real Time Executive
SFWE	Static Feed Water Electrolysis
SFWEM	Static Feed Water Electrolysis Module
SFWES	Static Feed Water Electrolysis Subsystem
SOC	Space Operations Center
3-FPC	Three Fluid Pressure Controller
TSA	Test Support Accessories
WEM	Water Electrolysis Module
WES	Water Electrolysis Subsystem

SUMMARY

Regenerative processes for the revitalization of spacecraft atmospheres are essential for realization of long-term space missions. These processes include oxygen generation through water electrolysis. The Static Feed/Alkaline Electrolyte Water Electrolysis concept has evolved over the past 15 years under National Aeronautics and Space Administration and Life Systems, Inc. sponsorship. This design has been recognized as capable of reliable oxygen generation with few subsystem components. A complete, self-contained water electrolysis subsystem based on this concept was developed and tested under the previous Contract, NAS2-10306. The objectives of the present program, a follow-on activity to NAS2-10306, were to: (1) demonstrate the performance, reliability and lower power requirements of the previously-developed Oxygen Generation Subsystem by endurance testing the subsystem, (2) evaluate the performance and reliability of the previously-developed 3-Fluid Pressure Controller through an independent extended endurance test, (3) design, develop and evaluate the performance a Water Electrolysis Subsystem Fluid Control Assembly, (4) investigate and demonstrate a unitized core/composite cell concept for use in static feed electrolysis cells, (5) demonstrate at the module level the concept of elimination of electrolyte in the static feed compartment of water electrolysis cells, (6) and evaluate, select and demonstrate a technique for minimizing or eliminating the use of nitrogen as a purge gas during the standby mode of operation of a water electrolysis subsystem.

The previously developed one-person level Oxygen Generation Subsystem, called the WS-1, was endurance tested. Production of the one-person oxygen metabolic requirement, 0.82 kg per day (1.81 lb per day), was demonstrated. During 2,980 hrs of endurance testing, cell voltages averaged 1.61 V at 206 mA/cm^2 (191 ASF) at an average operating temperature of only 326 K (128 F), virtually corresponding to the state-of-the-art performance previously established for single cells at Life Systems. This high efficiency—and therefore, low waste heat generation—prevented maintenance of the 339 K (150 F) design temperature without supplemental heating. Further evaluation of the subsystem is recommended as a follow-on effort.

The improved 3-Fluid Pressure Controller developed under the previous Contract was independently endurance tested for an extended period. This controller, which regulates the overall subsystem operating pressure as well as the differential pressures that must be maintained within the cell, demonstrated excellent regulation and smooth transitions during 8,650 hrs of operation. This included more than 7,400 simulated subsystem pressurization/depressurization cycles. Further weight, volume and minor configurational modifications are recommended for the next generation unit.

A Water Electrolysis Subsystem Fluid Control Assembly was designed, developed and evaluated. This single component, which replaces 18 separate fluid-handling components in a Water Electrolysis Subsystem, monitors and controls the flow of hydrogen and oxygen gases, controls and filters the supply of nitrogen for purging hydrogen and oxygen from the water electrolysis module, controls and filters the supply of water to the subsystem and monitors water differential pressure across the water storage tank.

An independent, 30-day cyclic test was performed. The Fluid Control Assembly effectively and successfully demonstrated fluid-flow control. This testing included transitions through 219 operating cycles and 432 water fill sequences. Extended testing and evaluation of the Fluid Control Assembly is recommended as a follow-on effort.

A Static Feed Water Electrolysis Unitized Core/Composite Cell concept was developed and tested. This concept, which combines a number of components within the static feed water electrolysis cell into a single, discrete unitized core, demonstrated the capability of withstanding differential pressures in excess of 210 kPa (30 psid) and, although not required for baseline operation, demonstrated static feed water electrolysis cell operational capabilities at differential pressures up to 85 kPa (12 psid). This composite cell design is projected to further simplify and improve the operational reliability of future Oxygen Generation Subsystems.

A Static Feed Water Electrolysis Module which requires no electrolyte in the static feed compartment was successfully demonstrated. This concept, which permits the feed water to double as the cell coolant and was initially developed and tested at the single-cell level under the previous Contract, is part of the continuing evolution towards significant reduction of future Oxygen Generation Subsystem complexity.

A technique to eliminate the use of nitrogen gas during the standby operating mode of a water electrolysis subsystem was evaluated and demonstrated. This alternate purge/pressurization technique consisted of the intermittent application of a low-level current to generate sufficient oxygen and hydrogen gas to offset pressure decays brought about by gas diffusion through the gas separator matrix and subsequent hydrogen/oxygen recombination effects. A 500 mA current applied to a Static Feed Water Electrolysis Module in cycles of three minutes on/four minutes off effectively maintained hydrogen and oxygen differential pressures and subsystem pressure at acceptable levels without the use of nitrogen gas. Evaluation of this technique under full subsystem cyclic operating conditions is recommended as a follow-on effort.

ACCOMPLISHMENTS

The key program accomplishments were as follows:

- Refurbished the WS-1 oxygen generation subsystem and successfully demonstrated a total of 2,980 hrs of normal operation.
- Achieved sustained one-person level oxygen generation performance with state-of-the-art cell voltages averaging 1.61 V at 206 mA/cm^2 (191 ASF) for an operating temperature of 326 K (128 F) (equivalent to 1.51 V when normalized to 355 K (180 F)).
- Endurance tested the 3-Fluid Pressure Controller for 8,650 hrs and successfully demonstrated the reliable performance capabilities.
- Designed and developed a Water Electrolysis Subsystem Fluid Control Assembly and demonstrated performance capabilities and reliability. Included was fabrication of two Fluid Control Assemblies and design and fabrication of a Water Electrolysis Subsystem Fluid Control Assembly test stand and associated Test Support Accessories.
- Developed and demonstrated at both the single cell and module levels a static feed water electrolysis unitized core/composite cell that provides expanded differential pressure tolerance capability, a key step in significantly increasing the simplicity and reliability of future Oxygen Generation Subsystem units.
- Fabricated and evaluated a feed water electrolyte elimination five-cell module. Included was the design and fabrication of a multi-functional high pressure/high temperature test stand and associated Test Support Accessories.
- Successfully evaluated and demonstrated a water electrolysis module pressurization technique which can be used in place of nitrogen gas during the standby mode of operation to maintain system pressure and differential pressures.

INTRODUCTION

Regenerative processes for the revitalization of spacecraft atmospheres are essential for making long-term manned space missions possible. An important step in this overall process is the generation of oxygen (O_2) for metabolic consumption through the electrolysis of water. The by-product hydrogen (H_2) is used to regenerate water from expired carbon dioxide (CO_2).[1] The water is then electrolyzed to generate additional O_2, etc.

An Oxygen Generation Subsystem (OGS) based on the static feed water electrolysis (SFWE) concept and using an alkaline electrolyte has been recognized as a designcapable of efficient, reliable O_2 generation with few subsystem components. The static feed concept has evolved over the past 15 years under National Aeronautics and Space Administration (NASA) and Life Systems, Incorporated.

This report presents the test results and associated development work on the self-contained OGS. The subsystem, termed the WS-1, generates 0.82 kg/d (1.81 lb/d) of O_2, equivalent to the metabolic needs of one person. This subsystem, the first complete self-contained SFWE subsystem, enables projection of static feed technology-based hardware for future spacecraft applications, such as that needed for the Space Operations Center (SOC).

Background

The technological concepts and prior performance on which the present subsystem is based are described below.

Static Feed Water Electrolysis Concept

Detailed descriptions of the static feed process, its theory of operation and its performance have been discussed previously.[2, 3, 4] The following subsections briefly summarize the subsystem and cell level concepts and the electrochemical reactions involved.

Basic Process. Within a water electrolysis cell, water is broken apart into its component elements by supplying electrons to the H_2 at a negatively charged electrode (cathode) and removing electrons from the O_2 at a positively charged electrode (anode). The half-cell reactions are as follows for water electrolysis cells using an alkaline electrolyte:

At the cathode:

$$2H_2O + 2e^- = H_2 + 2OH^- \qquad (1)$$

At the anode:

$$2OH^- = 1/2O_2 + 2e^- + H_2O \qquad (2)$$

These result in the overall reaction of:

$$\text{Electrical Energy} + H_2O = H_2 + 1/2O_2 + \text{Heat} \qquad (3)$$

(1) Superscripted numbers in parenthesis are citations of references listed at the end of this report.

The Static Feed Water Electrolysis Cell. The extent to which these reactions can be used for practical O_2/H_2 generation is, however, highly dependent on cell technology. Figure 1 is a functional schematic of a SFWE cell. Initially, both the water feed cavity and the cell matrix have equal concentrations of electrolyte. As electrical power is supplied to the electrodes, water is electrolyzed from the cell matrix creating a concentration gradient between the electrolyte in the water feed cavity and the electrolyte in the cell matrix. Water vapor diffuses from the water feed matrix into the cell matrix due to this gradient. Consumption of water from the water feed cavity results in its static replenishment from an external water supply tank. Major advantages are that:

1. No moving parts are required since the water feed mechanism is entirely passive and self-regulating based upon the demands of the electrolyzer.
2. No liquid/gas separators are needed.
3. Virtually no feed water pretreatment is needed, because contact between the liquid feed water and the cell electrodes does not occur, thus preventing feed water contaminants from poisoning the electrode catalyst.

These features contribute to simple operation and long life. As shown in Figure 1, waste heat generated by the electrochemical reaction is removed by the liquid coolant circulating through a compartment adjacent to the O_2 generation cavity. The N_2 purge, not used during normal cell operation, pressurizes and depressurizes the cell during startup and shutdown,respectively. It is also used to maintain pressure during the standby mode.

Subsystem Concept

The basic cells are combined with supporting components to form the subsystem. A functional schematic of a static feed water electrolysis-based OGS is shown in Figure 2. The mechanical portion of the subsystem consists principally of three components: an electrochemical module, a Coolant Control Assembly (CCA) and a Three-Fluid Pressure Controller (3-FPC). The CCA and 3-FPC are special components developed for use with a static feed OGS. The module consists of a series of individual electrochemical cells stacked fluidically in parallel and connected electrically in series to form the Static Feed Water Electrolysis Module (SFWEM). Oxygen and H_2 are generated in the SFWEM from water supplied by the water supply tank. The CCA (1) supplies a constant flow of controlled, variable temperature liquid coolant to the SFWEM, (2) proportions the coolant flow between a by-pass and a liquid/liquid heat exchanger, and (3) accommodates temperature-induced volume changes in the coolant. The 3-FPC (1) maintains the absolute pressure of the subsystem, (2) controls the pressure differentials required to establish and maintain liquid/gas interfaces within the individual cells, and (3) controls pressurization and depressurization of the subsystem during mode transitions (e.g., start-ups and shutdowns).

An automatic Control/Monitor Instrumentation (C/M I) unit supplies current to the electrolysis module and regulates and monitors the performance of the entire subsystem. Additionally, a Water Electrolysis Subsystem Fluid Control Assembly (WES FCA) has been designed for integration into the OGS. This lightweight, Line Replaceable Unit replaces 18 additional fluid-handling components (valves, pressure transducers, etc.) which control and monitor OGS water and nitrogen purge gas supplies and pressures.

State-of-the-Art Cell Performance Base

The key performance-indicating parameter of an OGS is the voltage of the individual cells, because the power required to produce O_2 at a given rate is directly proportional to that voltage.

Oxygen Generation Subsystem development activities at LSI resulted in substantial improvements in operating cell voltages at practical current density levels. These reductions were achieved primarily by reducing the overvoltage at the O_2-evolving electrode (anode). Operation with improved anodes was previously characterized at cell and module levels.[4]

These results provided a design basis for the cells of the WS-1 module.

Program Objectives

The primary objectives of the subject program were to:

1. Demonstrate SFWE-based OGS reliability and acceptability through endurance testing of the one-person capacity OGS (the WS-1) and its product gas/feed water pressure controller (3-FPC).
2. Design, fabricate and evaluate a Fluid Control Assembly (FCA) which demonstrates simplification of the OGS through the grouping of individual fluid handling components into a single unit.
3. Demonstrate electrolysis cell performance reproducibility through a unitized core/composite cell development.
4. Demonstrate, at the module level, the simplification of the OGS's water feed mechanism and N_2 purge pressurization requirements.

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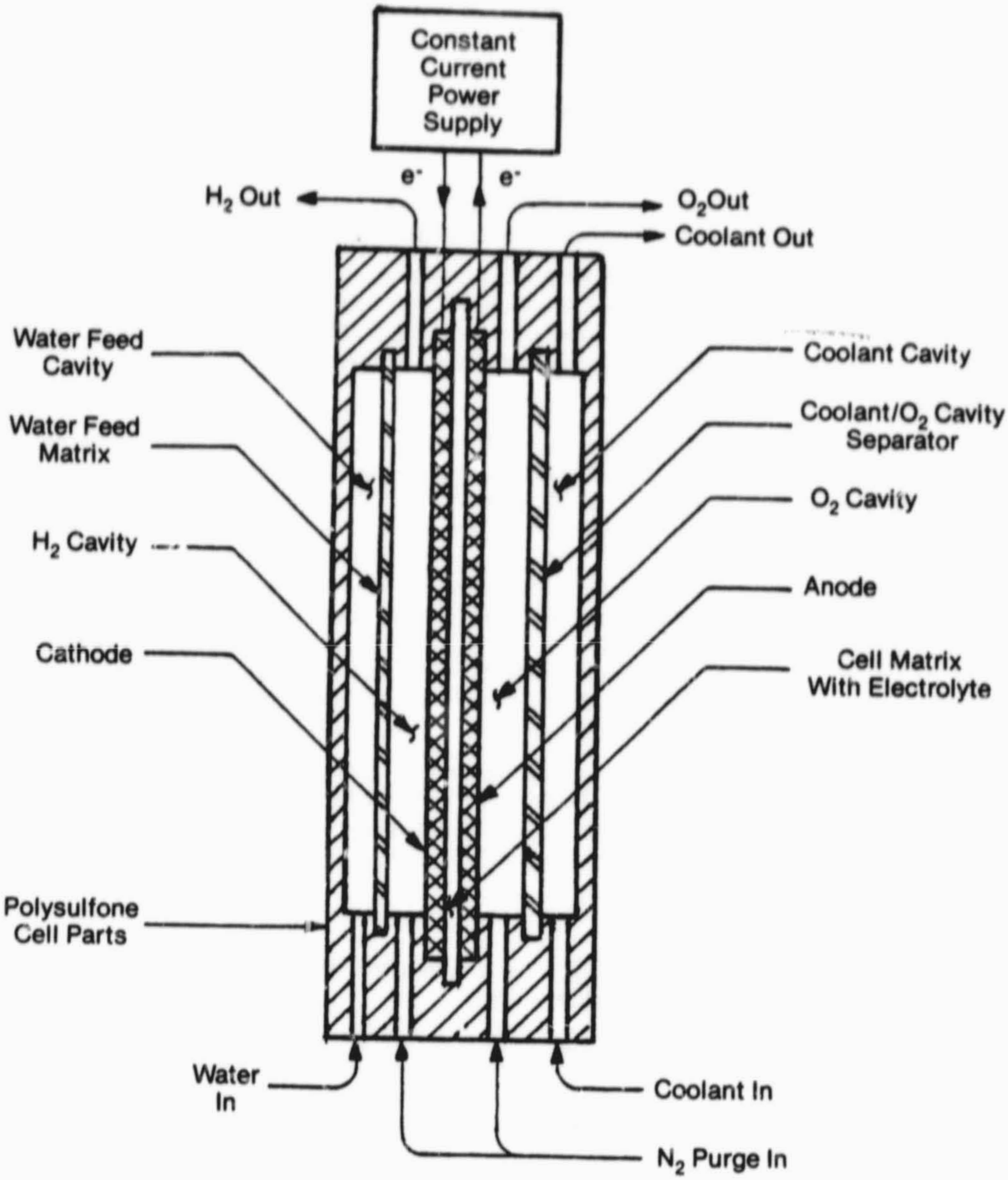

FIGURE 1 CELL FUNCTIONAL SCHEMATIC

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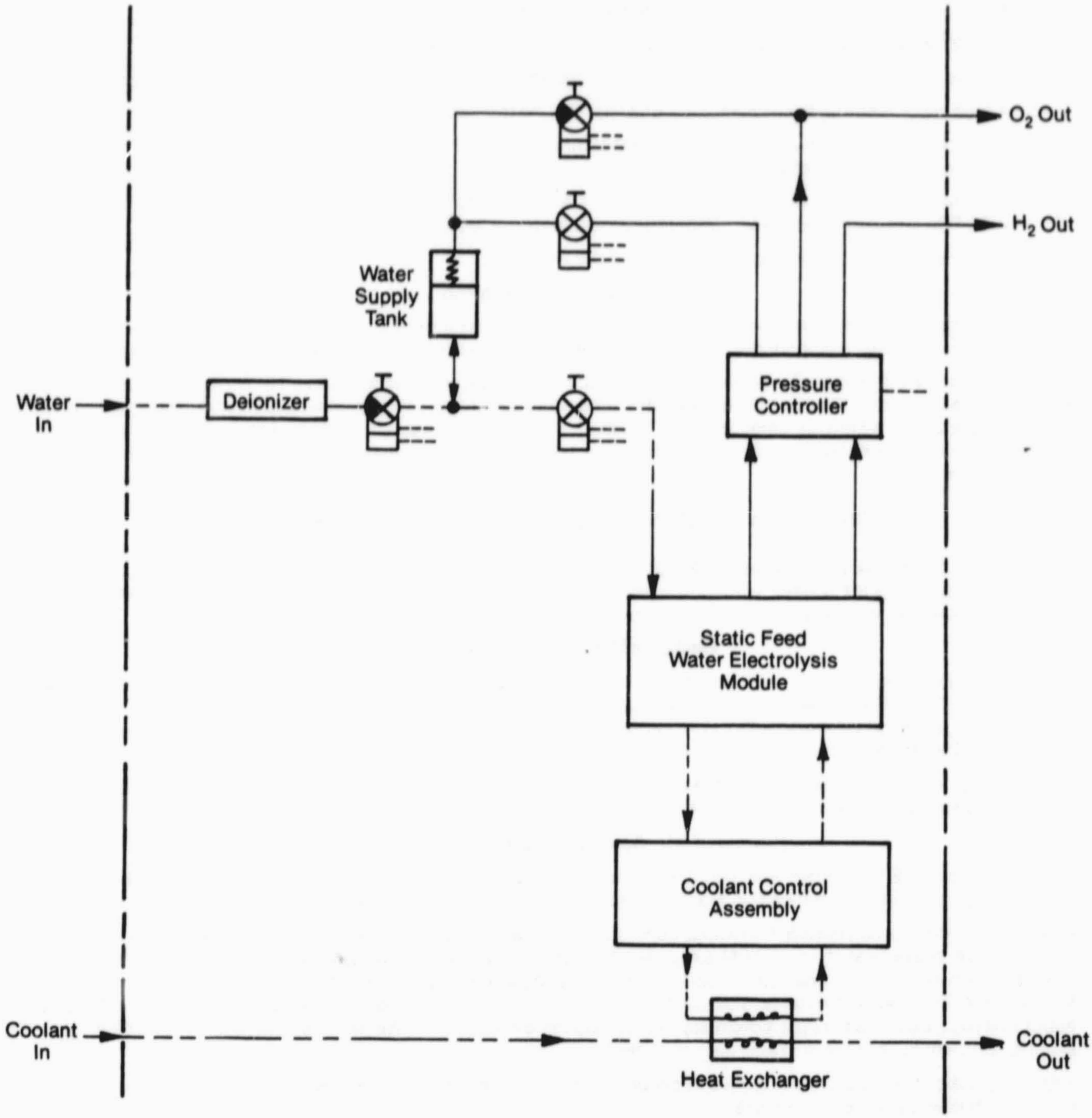

FIGURE 2 STATIC FEED WATER ELECTROLYSIS SUBSYSTEM FUNCTIONAL SCHEMATIC

End Items

The following end items were developed as a result of the subject program activities:

1. Oxygen Generation Subsystem (WS-1) endurance test data.
2. Three-Fluid Pressure Controller (3-FPC) endurance test data.
3. Two (2) Water Electrolysis Subsystem Fluid Control Assemblies (WES FCAs).
4. A static feed water electrolysis unitized core/composite cell design and single-cell and six-cell module test results.
5. A feed water electrolyte elimination six-cell module and test results.
6. A concept for the alternate purge/pressurization of a static feed water electrolysis module operating in the standby mode and technique demonstration test results.
7. Test support accessories to evaluate the WES FCA and the feed water electrolyte elimination module, including a WES FCA test stand and a high temperature/high pressure test stand.
8. Documentation of the progress and results of the effort.

Report Organization

The WS-1 Subsystem endurance test results are presented following a review and discussion of the O_2 generation subsystem design and major components. A discussion of the 3-FPC and its endurance test results are then presented.

Related advanced technology efforts are then discussed, including development of the WES FCA, development of the static feed water electrolysis unitized core/composite cell, feed water electrolyte elimination six-cell module testing and alternate purge/pressurization technique demonstration. Finally, a mini-Product Assurance effort instituted during the program is described briefly, followed by conclusions drawn from the subject effort, recommendations for future efforts and references cited in the text.

ONE-PERSON OXYGEN GENERATION SUBSYSTEM (WS-1) ENDURANCE TEST

The first section of this chapter reviews the design objectives for the WS-1 and some general characteristics that apply to the overall subsystem. This is followed by brief reviews and discussions of the the Mechanical/Electrochemical Assembly (M/E A), the C/M I, the test support accessories and, finally, the WS-1 endurance test program.

Review of WS-1 Subsystem Design

The overall Subsystem design is shown pictorially in Figure 3 and schematicallyin Figure 4. Table 1 lists the WS-1 design specifications. The M/E A contains the water electrolysis module and all supporting fluid handling components, including the 3-FPC, a CCA, solenoid valves, etc. The C/M I controls all operations of the M/EA and provides for monitoring of critical parameters. Therefore, as shown in Figure 4, these two assemblies are interactive.

The WS-1 has four different operating modes as illustrated in Figure 5 and defined in Table 2. Nine different transitions between the operational mode are permissible and programmed into the C/M I.

Review of Mechanical/Electrochemical Assembly

The M/E A of a SFWE Subsystem was described generally in Figure 2. Specifically, the M/E A of the WS-1 is illustrated pictorially in Figure 6 and schematically in Figure 7. Its weight and power requirements are listed in Tables 3 and 4.

Figure 7 illustrates the functions of the various components. The electrochemical module, shown in Figure 8, is liquid-cooled using the CCA. Waste heat of the SFWEM is rejected through the CCA coolant to an external liquid coolant loop via a liquid/liquid heat exchanger. Product gas pressures and the water supply tank and CCA accumulator reference pressures are controlled by a 3-FPC. The feed water is cyclically replenished through automatic filling of the water supply tank. No feed water pump is needed, because the tank is depressurized during filling and spacecraft water supply pressure (typically 207 kpa (30 psia)) is sufficient to fill the tank in less than one minute.

A deionizer cartridge is included in the water supply line to remove dissolved carbon dioxide (CO_2). A safety N_2 purge is included, with flow rates fixed by orifices.

Water Electrolysis Module

As described previously, the water electrolysis cells are the heart of the subsystem. The module for the WS-1, previously shown in Figure 8, is comprised of six state-of-the-art SFWE cells. The assembled module weighs 25.5 kg (56 lbs), using non-optimized end plates. The weight of each cell is 0.71 kg (1.56 lbs). For purposes of scale-up, this means 4.3 kg (9.4 lbs) of cell hardware are required to produce the metabolic O_2 required by one person.

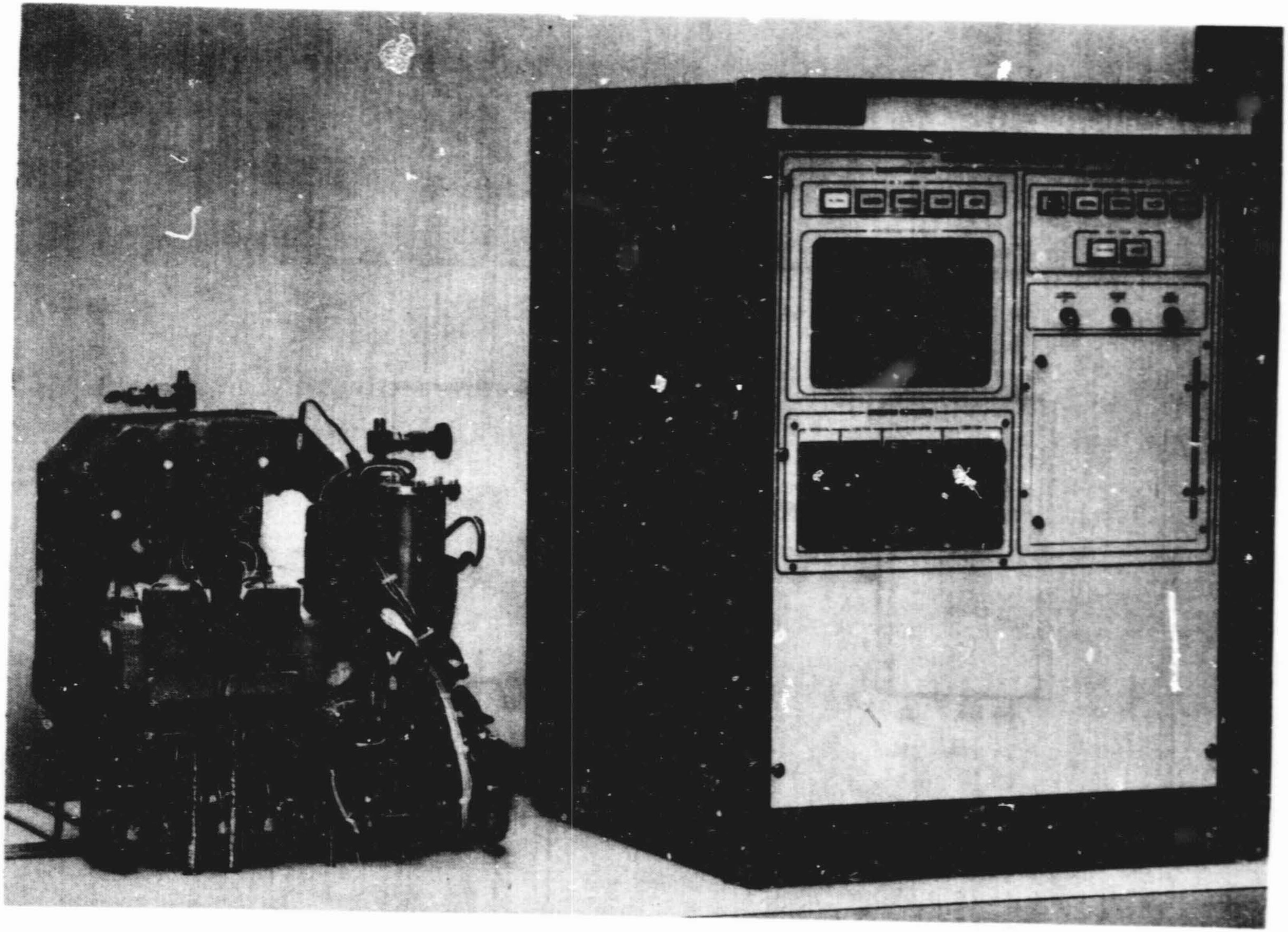

FIGURE 3 WS-1 MECHANICAL/ELECTROCHEMICAL PACKAGE
WITH CONTROL/MONITOR INSTRUMENTATION

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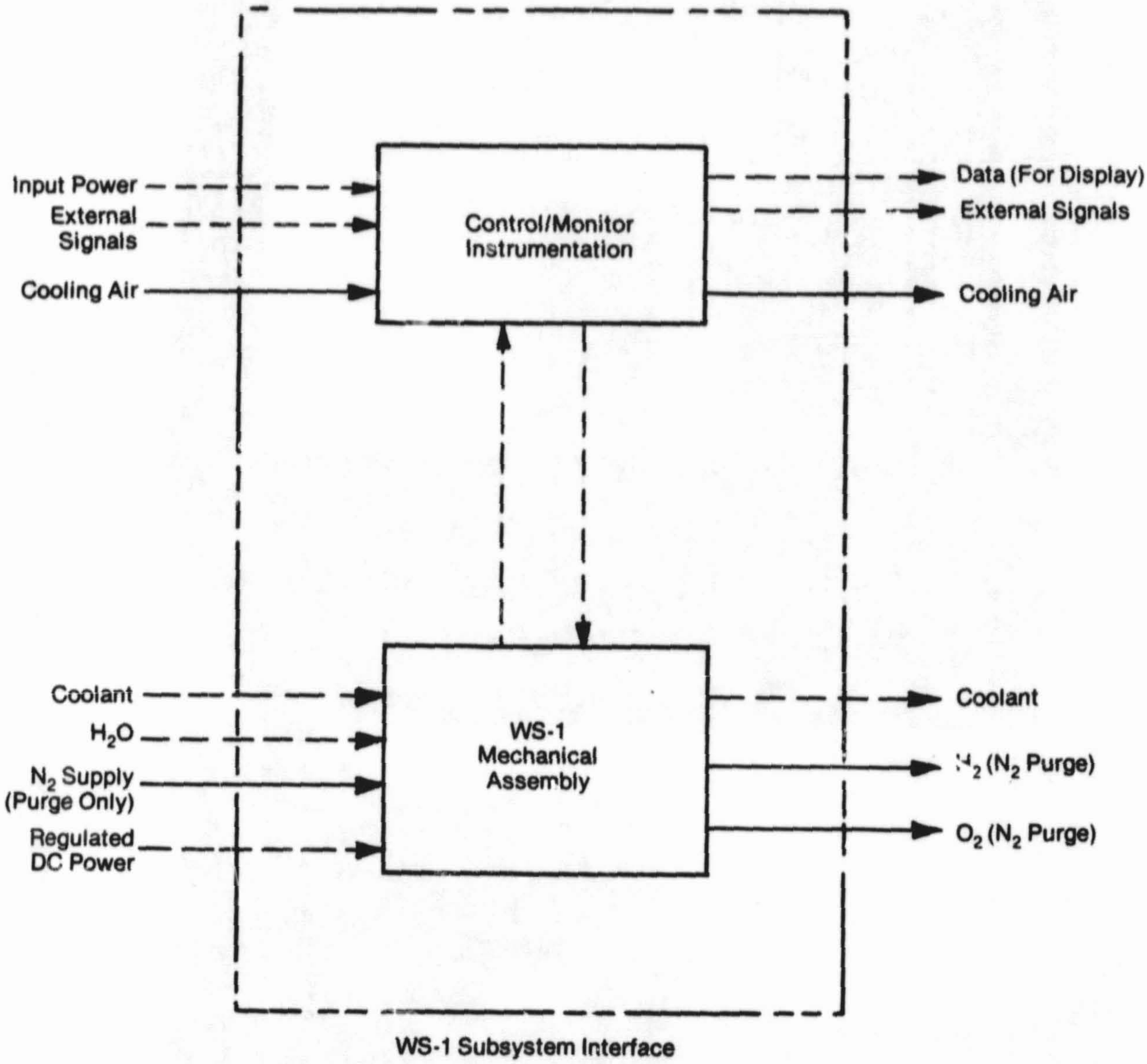
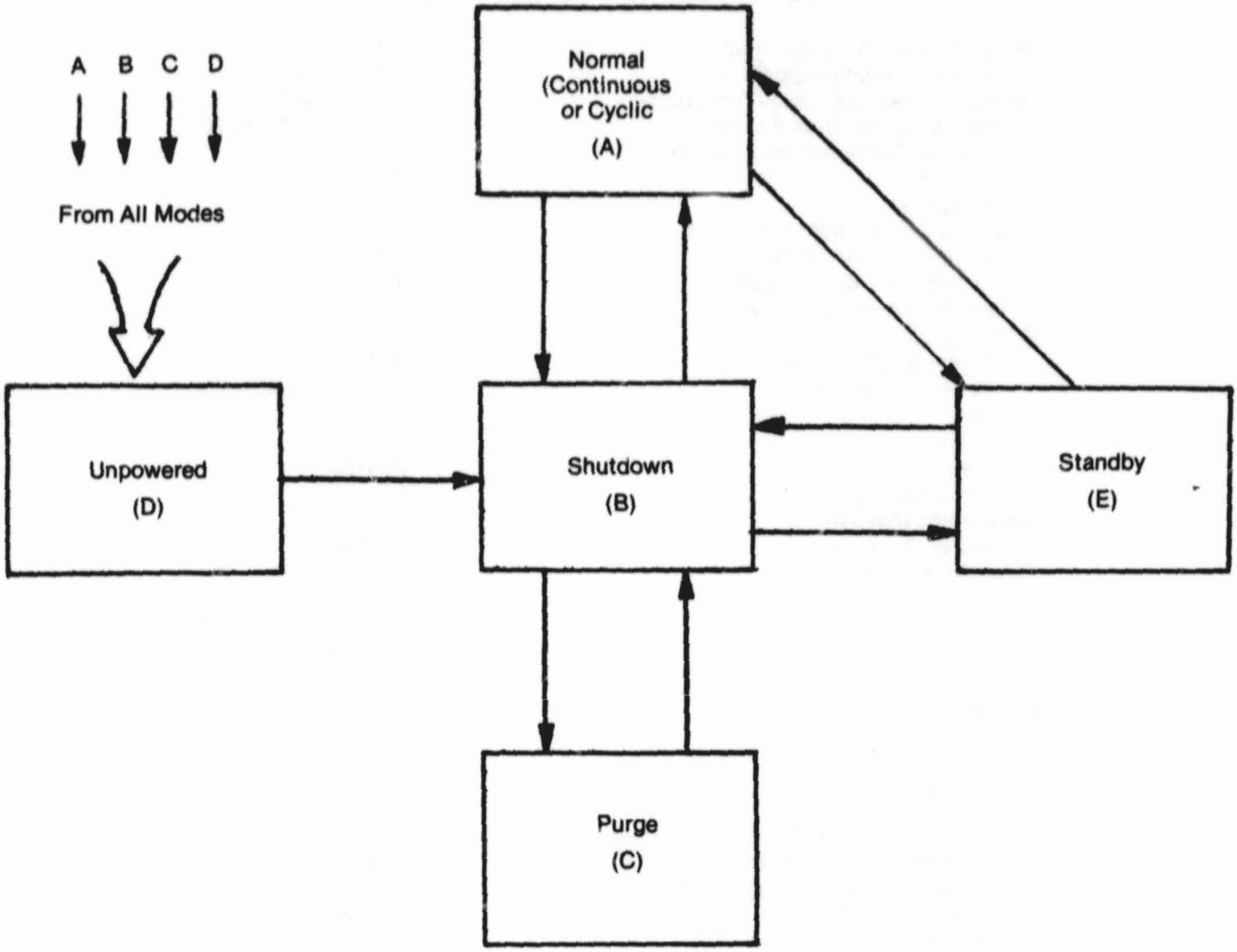


FIGURE 4 WS-1 PROCESS BLOCK DIAGRAM

TABLE 1 WS-1 DESIGN SPECIFICATIONS

H_2 Generation Rate, kg/d (lb/d)	0.103 (0.23)
O_2 Generation Rate, kg/d (lb/d)	0.82 (1.81)
Operating Pressure Range, kPa (psia)	103 to 1,482 (15 to 215)
Operating Temperature Range, K (F)	294 to 366 (70 to 200)
Pressure Differentials (max.), kPa (psid)	
O_2 to H_2	21 (3.0)
H_2 to H_2O	21 (3.0)
Performance ($\pm$ 0.005), V per Cell	
At 108 mA/cm^2 (100 ASF)	1.44
At 162 mA/cm^2 (150 ASF)	1.48
At 324 mA/cm^2 (300 ASF)	1.56
Water Supply	
Pressure, kPa (psia)	207 (30)
Temperature, K (F)	277 to 300 (40 to 80)
Coolant	
Fluid	Water
Pressure, kPa (psia)	205 (30)
Temperature, K (F)	322 (120)
Water Feed Mechanism	Static
Active Cell Area, cm^2 (ft^2)	93 (0.10)
Electrical Power, V	
DC	28
AC	115/200 (400 Hz, 3 Phase) 115 (60 Hz, 1 Phase)
Purge Supply	
Type Gas	N_2
Pressure, kPa (psia)	1,255 (182)
Packaging	
Style	Self-Contained
Volume (Mechanical/Electrochemical), m^3 (ft^3)	0.11 (3.8)
Volume (Electrical/Electronic), m^3 (ft^3)	0.20 (7.2)
Weight (Mechanical/Electrical), kg (lb)	182 (400)
Allowable Downtime, h	8 to 48
Duty Cycle	Continuous/Cyclic



- 5 Modes
- 4 Operating Modes
- 13 Mode Transitions
- 9 Programmable, Allowable Mode Transitions

FIGURE 5 WS-1 MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 2 WS-1 OPERATING MODES AND UNPOWERED MODE DEFINITIONS

Mode (Code)	Definition
Shutdown (B)	The WS-1 is not generating O_2 and H_2. Module current is zero and the system is depressurized and at ambient temperature. All valves are deactivated except the N_2 purge valves V4 and V5. The subsystem is powered and all sensors are working. The Shutdown Mode is called for by: • Manual actuation • Low H_2O Feed Pressure • High WEM Temperature • High Subsystem Pressure • Low Subsystem Pressure • High WEM Cell Voltage • Low WEM Cell Voltage • Power on reset (POR) from Unpowered Mode (D) • Mode transition from Shutdown Mode (B) to Normal (A), Standby (E), or Purge (C) was not successful. All transitions to the Shutdown Mode except POR and Purge include a timed purge sequence as part of the mode transition sequence.
Normal (A) (Continuous/Cyclic)	The WS-1 is performing its function of generating O_2 at the one-person rate. The subsystem is at temperature and pressure. The Normal Mode is called for by: • Manual actuation • Incomplete transition from Normal (A) to Standby (E) Mode The WS-1 can operate continuously or cyclically.
Standby (E)	The WS-1 is ready to generate H_2 and O_2. The subsystem is powered and all valves are at running position except the N_2 purge valves V4 and V5, which are open to maintain subsystem pressure. The module current is off. The standby Mode is called for by: • Manual actuation • Incomplete transition from Standby (E) to Normal (A) Mode
Purge (C)	The WS-1 is being purged with N_2 through the gas lines and compartments. Module current is off and the H_2O inlet valve is closed. The subsystem is at low pressure and the temperature is ambient. This is a continuous purge until a new mode is called. The Purge Mode is called for by: • Manual actuation
Unpowered (D)	No electrical power is applied to the WS-1. Actuator positions can only be verified visually. There will be no water flow. There will be N_2 purge flow unless the TSA has a shutoff valve to control the N_2 feed. The Unpowered Mode is called for by: • Manual actuation (circuit breaker in TSA) • Electrical Power failure • C/M I failure as detected by the external Supplementary Shutdown Controller

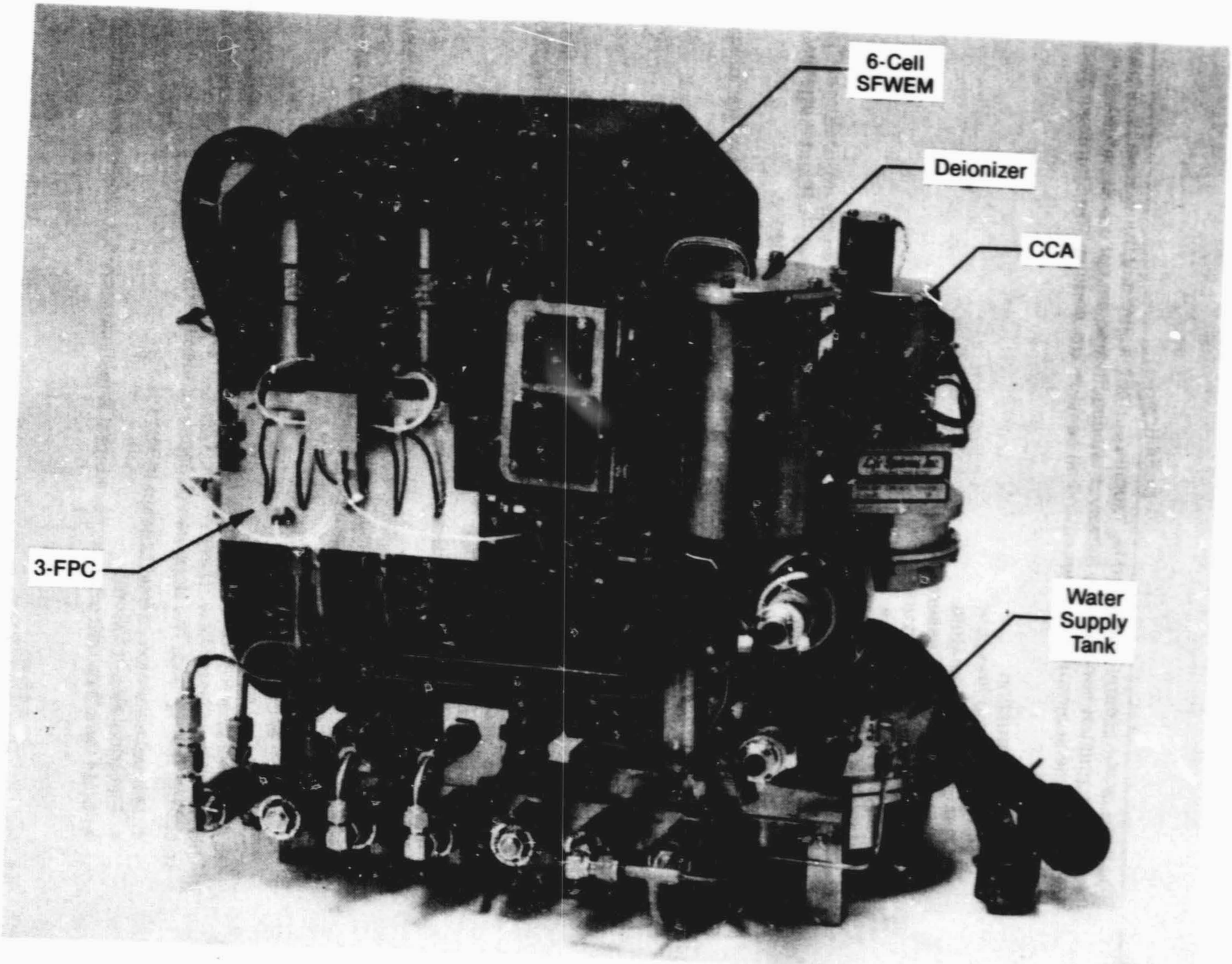


FIGURE 6 WS-1 MECHANICAL/ELECTROCHEMICAL ASSEMBLY

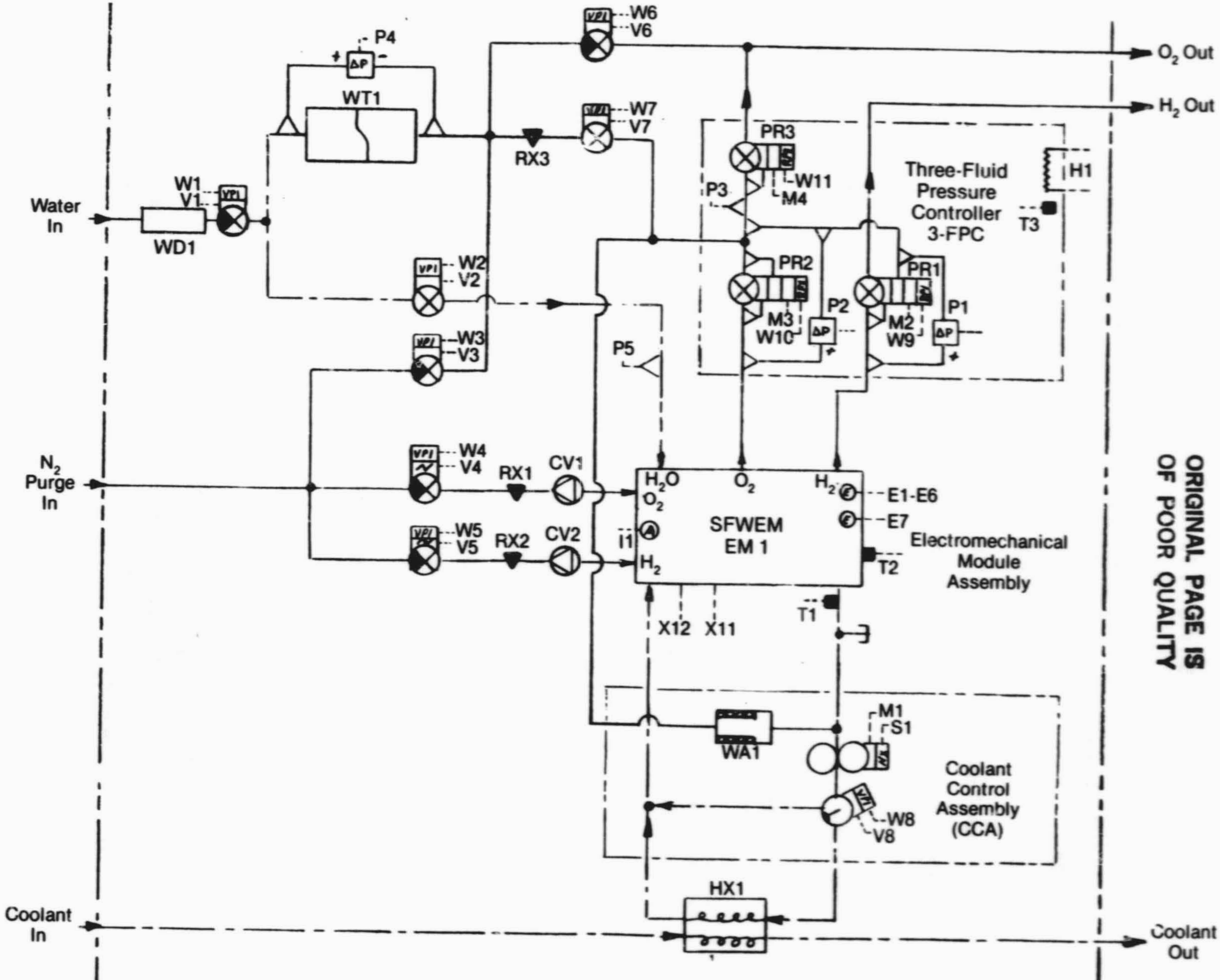


FIGURE 7 WS-1 MECHANICAL SCHEMATIC

TABLE 3 WS-1 COMPONENT CHARACTERISTICS

Component	Weight, kg (lb)	Power, W AC	Power, W DC	Heat Rejection, W
SFWEM	25.5 (56.0)[a]	—	205[b]	36
3-FPC	4.9 (10.7)		20	20
Water Feed Tank	3.4 (7.5)	—	—	—
Heat Exchanger	0.7 (1.5)	—	—	—
CCA	4.2 (9.3)	20	—	20
Deionizer	2.0 (4.4)	—	—	—
Ancillary Components and Packaging	6.8 (15.0)	—	16	16
Total	47.5 (104.4)	20	241	92

(a) An 11.4 kg (25.0 lb) reduction is possible using state-of-the-art honeycomb endplates.
(b) Including losses due to 85% power conversion efficiency.

TABLE 4 WS-1 TOTAL EQUIVALENT WEIGHT FOR SPACECRAFT APPLICATION

Fixed Hardware Weight, kg (lb)	47.5 (104.4)
Power Penalty,[a] kg (lb)	
AC	6.5 (14.2)
DC	64.4 (142.2)
Heat Rejection Penalty,[b] kg (lb)	13.9 (30.5)
Total, kg (lb)	132.3 (291.3)

(a) Based on 0.322 kg/W (0.710 lb/W) power penalty for AC power and 0.268 kg/W (0.590 lb/W) for DC power.
(b) Based on 0.198 kg/W (0.436 lb/W) heat rejection penalty for rejection directly to cabin air and 0.083 kg/W (0.184 lb/W) for rejection to liquid coolant loop.

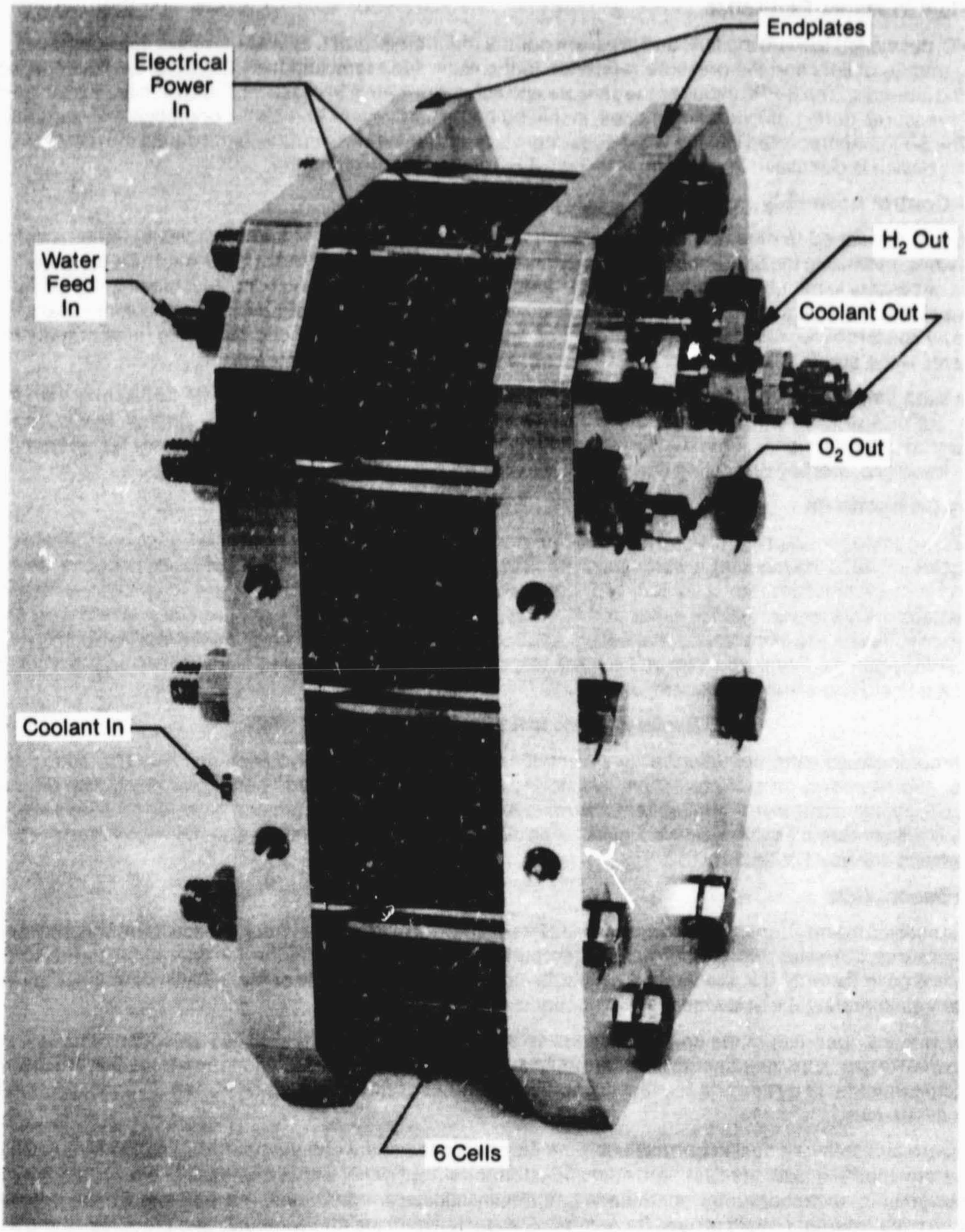


FIGURE 8 SIX-CELL WATER ELECTROLYSIS MODULE

Three-Fluid Pressure Controller

The 3-FPC, developed to meet the fluid and pressure control requirements of a SFWEM, has five fluid interfaces: H_2 and O_2 inlets, H_2 and O_2 outlets and the pressure reference to the water feed tank and the CCA. All other fluid connections are manifolded internally. The 3-FPC includes the sensors and actuators necessary to control and monitor fluid absolute and differential pressures during all operating modes, including both steady state and cyclic operation and startups and shutdowns. The 3-FPC incorporated into the WS-1 subsystem is an improved version developed during the previous contractual effort. This device is discussed in more detail in the 3-FPC endurance test chapter.

Coolant Control Assembly

The CCA was developed to meet the temperature control needs of the SFWEM and other liquid-cooled electrochemical modules while minimizing the Subsystem complexity.[6] The CCA combines, in a single-integrated assembly, the sensors and actuators necessary to maintain a constant, preset module temperature despite varying heat loads of the module. The CCA contains a motor, a pump, a motor-actuated mixing valve, an accumulator to compensate for coolant expansion and contraction and sensors to register the speed of the pump and the position of the mixing valve. The three primary mechanical components—the pump, valve and accumulator—were shown schematically in Figure 7.

It can be seen that the CCA has four liquid interface connections: to and from the SFWEM and to and from the heat exchanger. The CCA regulates temperature of the module by varying the ratio of coolant flow through the heat exchanger to that through an internal bypass. Both the pump motor and the valve positioning motor can be easily replaced without breaking into a liquid line, thereby promoting component maintenance.

Ancillary Components

The ancillary components consist essentially of a deionizer to remove CO_2 from the water (to prevent carbonate formation in the basic electrolyte of the module), a water supply tank to feed water to the SFWEM at operating pressure, seven solenoid valves to control system operation, a liquid/liquid heat exchanger and standard temperature and pressure sensors. No condensor/separators are required, since expansion from the operating pressure of the gas product to ambient pressure lowers the dewpoint sufficiently to eliminate condensation. Additionally, the static water feed principal eliminates the need for water feed circulating pumps. Finally, cooling of the product gases during expansion and temperature equilibration in the subsystem are sufficient to eliminate exchangers.

Review of Control/Monitor Instrumentation

A minicomputer-based instrumentation hardware provides for parameter control, automatic mode and mode transition control, automatic shutdown for self-protection, monitoring of subsystem parameters and interfacing with data acquisition facilities. Life Systems' standard development instrumentation package, programmable to perform these functions, was used. The unit is illustrated in Figures 3 and 9. Figure 10 is a block diagram of the interactive sections and interfaces. The design characteristics are listed in Table 5.

General Description

The C/M I receives from or transmits signals to the M/E A sensors and actuators. Through these it controls and monitors subsystem pressures, flow rates, temperatures, voltages, currents and valve positions in each operating mode (shown in Figure 5 and described in Table 2). It implements each mode as initiated automatically or manually and provides fail-safe operational changes to protect the subsystem if malfunctions occur.

Internally, process operating mode control includes selection of different unit processes, selection of valve positions, sequencing of valve positions, sequencing of actuators and checking parametric conditions as a transition proceeds. This procedure is fully automated by the C/M I so that the operator only needs to press the Mode Change request buttons to initiate transition sequences.

The hardware and software design permits real-time communication between the operator and the M/E A. On the operator/subsystem interface side, the C/M I provides the operator a front panel with a keyboard and a cathode ray tube (CRT) display designed to accept operator commands and display subsystemmessages, respectively. On the process side, an analog and digital interface board is used for communication between the minicomputer and the sensors and actuators of the subsystem. A static trend analysis is included that compares parameter readings with setpoints that indicate Caution, Warning, and Alarm thresholds. Visual displays indicating whether a parameter is in the Normal, Caution, Warning or Alarm range are provided on the front panel.

Control algorithms/concepts are defined for specific subsystem parameters and sequences. Module current, module temperature, subsystem pressure, product gas pressure differentials and 3-FPC temperature are controlled to pre-set values using closed loop, feedback controls. Critical subsystem parameters are selected for monitoring to provide for automatic

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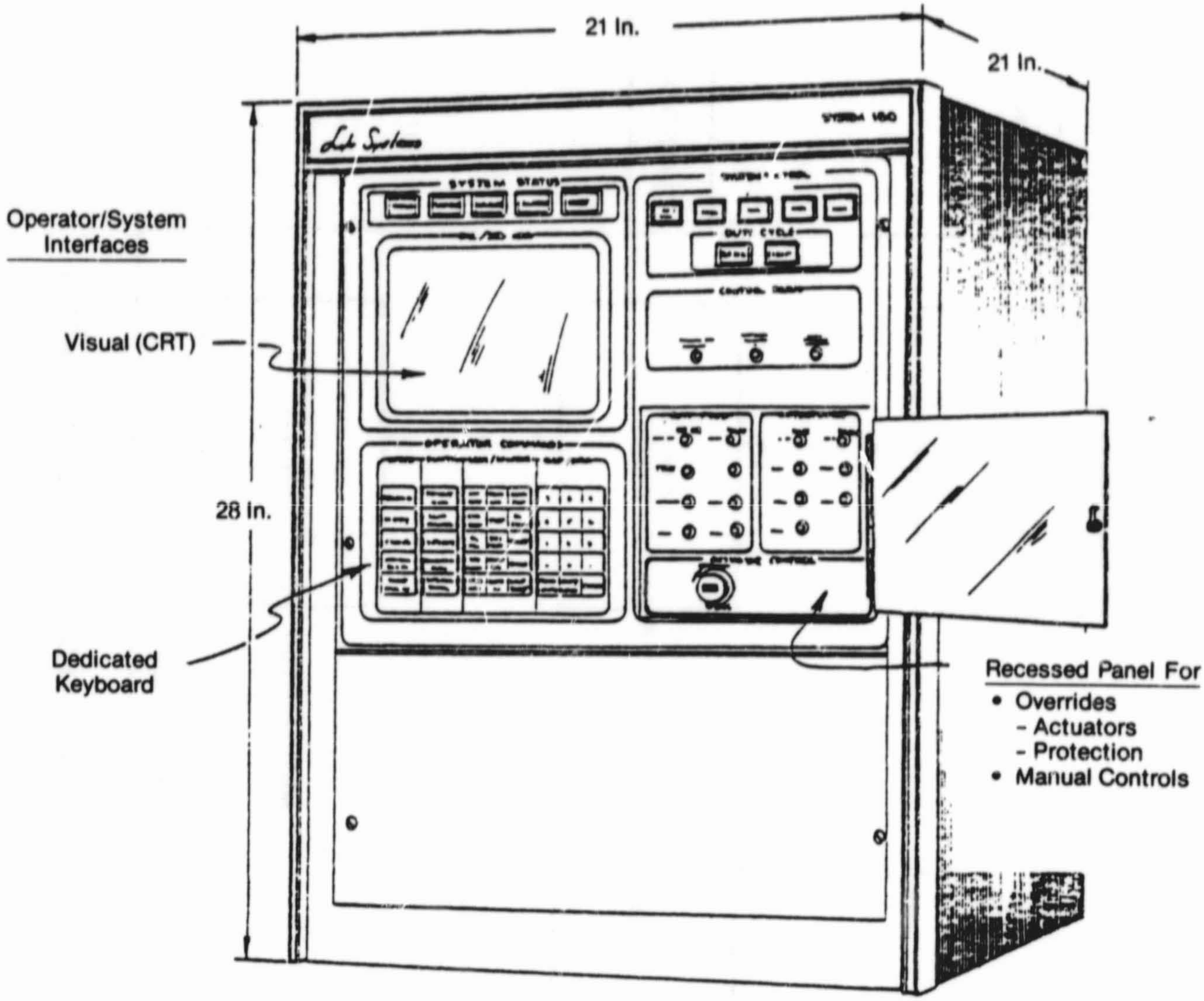

FIGURE 9 C/M I PACKAGE

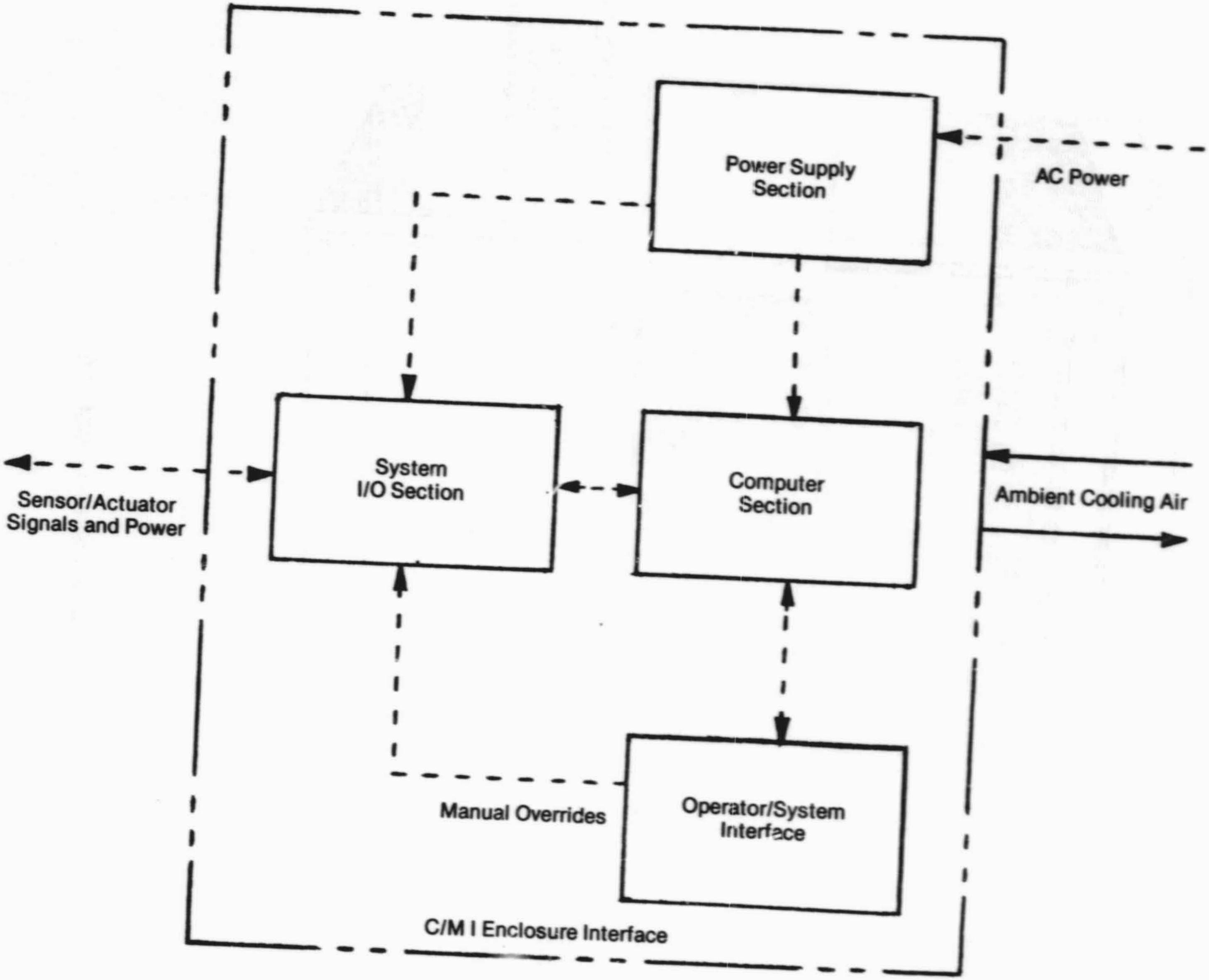

FIGURE 10 WS-1 C/M I HARDWARE FUNCTIONAL BLOCK DIAGRAM

TABLE 5 WS-1 CONTROL/MONITOR INSTRUMENTATION DESIGN CHARACTERISTICS

Dimensions (D x W x H), cm (in)	53.3 x 53.3 x 71.3 (21 x 21 x 28.6)
Weight, kg (lb)	102 (225)
Power Input, W	712
Power Consumption, W	522
Line Voltage, V	115, 1 Phase
Line Frequency, Hz	400 and 60
Input Sensor Signal Range, VDC	0 to 5
Output Actuator Signal Range, VDC	0 to 5
Processor	
Type of Computer	CAI LSI-2/20 Minicomputer
Word Size, Bits	16
Memory Size, K Words of Core	16
Memory Speed, ns	1200
Instruction Cycle Time, ns	150
I/O Transfer Rate, Megawords/s	1.67
Other Important Features	• Real Time Clock • DMA Channels • Hardware Multiply/Divide • Stack processing • Automatic and Blocked I/O • Power Fail Restart
Input/Output	
Number of Analog Inputs	17
Number of Analog Outputs	1
Number of Digital Inputs	16
Number of Digital Outputs	14
Front panel	
Command Inputs	Push Button Switches
Message Display	Color-Coded Indicators and CRT Display
Display CRT Capacity, Characters	1,920 (80 x 24)
Number of Manual Overrides	13
Operating Modes	
Number of Operating Modes	4
Number of Allowable Mode Transitions	9
Number of Normal Mode Duty Cycles	2

shutdown for self-protection. Shutdown levels were selected for above and/or below nominal operating values. Only temperatures and pressures are monitored during other than normal operation and during selected mode transitions.

Software

The software manages the entire operation of the C/M I as shown in Figure 11. The Power-Failure Control resets the system conditions when power is applied to the C/M I. The Real-Time Executive (RTE), driven by the real-time clock, is designed to execute different programs in a timely fashion. The Front Panel Command Handler allows the operator to communicate with the system through the front panel buttons. The Operating Mode control is designed to resolve all mode change requests in the system. Mode change requests, either manually generated or system, are checked by the Operating Mode Control module. The Mode Transition Control modules provide the necessary transition sequences from one operating mode to another. The Process Parameter Control and Monitor routines, which include open-loop program control, feedback on/off control, supervisory control, feedback proportional control and feedback proportional, integral and differential control, are designed for specific applications and operates under the RTE to maintain the parameters within specified ranges. The Fault Detection and Trend Analysis detects symptoms of component failures through sensors which are incorporated to monitor the key parameters of the system. When a parameter reaches a certain limit, the system shuts down to prevent any further irreversible damages. Normal, Caution, Warning and Alarm indicators are provided on the front panel. The Input/Output modules are under the RTE control. The input routine reads all data from the Analog to Digital Converter (ADC) channels and places them into the input buffer; the output routine transfers all the data in the output buffer to the output channels of the digital (I/O) interface. The DAS Handler provides for external communication with a data acquisition and reduction system for monitoring of process variables.

Review of Test Support Accessories

The C/M I subsystem of the WS-1 provides a large variety of parametric readouts in addition to controlling all aspects of the M/E A performance. Other test support accessories (TSA) include a Data Acquisition and Reduction System (DARS) to permit automatic recording of performance parameters and auxiliary equipment to supply and monitor fluids and power to the subsystem and provide redundant monitoring of certain key operational parameters. The required components are illustrated pictorially in Figure 12 and schematically in Figure 13. The DARS, developed under Life Systems' IRAD Programs and made available for automated data storage and retrieval during this test program, provides data retrieval, scaling and formal presentation by means of analog-to-digital converters, a minicomputer, dual diskette data storage and both CRT and line-printer readouts. The DARS is capable of recording data from up to 32 analog parametric inputs. The period between data sampling and storage can be adjusted from between one second to 18 hours. Use of the DARS permits unattended evaluation of the WS-1 and subsequent cost-effective retrieval and reduction of data. The fluid supply TSA includes: a purified water source (water tank, feed pumpand pressure gauge); a N_2 purge supply, including a N_2 pressure gauge; a coolant supply tank and pump; gauges for measuring O_2 pressure and O_2/H_2 differential pressure at the module; and a soap bubble flow meter for checking O_2 and H_2 outputs. Electrical TSA includes power supplies and analog meters for independent monitoring of individual cell voltages, module voltage and module current.

Test Program

The test program consisted of subsystem refurbishment activities, a brief subsystem checkout and endurance testing. The testing included 124 days of accumulated operation. A discussion of the test activities follows.

Subsystem Refurbishment

The WS-1 subsystem refurbishment activities undertaken prior to initiation of endurance testing are listed in Table 6.

Checkout Testing

Checkout Testing of the WS-1 was performed initially. This phase of the testing program included calibrations, mechanical and electrical integrity checks, and verification that components and subassemblies were correctly integrated and refurbishment activities were satisfactorily completed.

Endurance Testing

During endurance testing, the subsystem performance was observed over 2,980 hrs (approximately 124 days) of cumulative operation. The design O_2 production rate of 0.82 kg/day (1.81 lbs/day) at 206 mA/cm^2 (191 ASF) was verified. The low waste heat available in the module at the design current density was insufficient to maintain the design operating temperature of 339 K (150 F) because of high cell efficiency (i.e., low cell voltage). A steady-state average operating temperature of 326 K (128 F) was attained at an ambient temperature of 294 K (70 F). Cell voltages at these conditions averaged 1.61 V, as shown in Figure 14, virtually corresponding to the state-of-the-art performance previously reported. During the course of the endurance test program, eight subsystem shutdowns occurred (not including the final subsystem shutdown at test completion). These are indicated numerically on Figure 14. The shutdown descriptions and the actions taken are shown in Table 7.

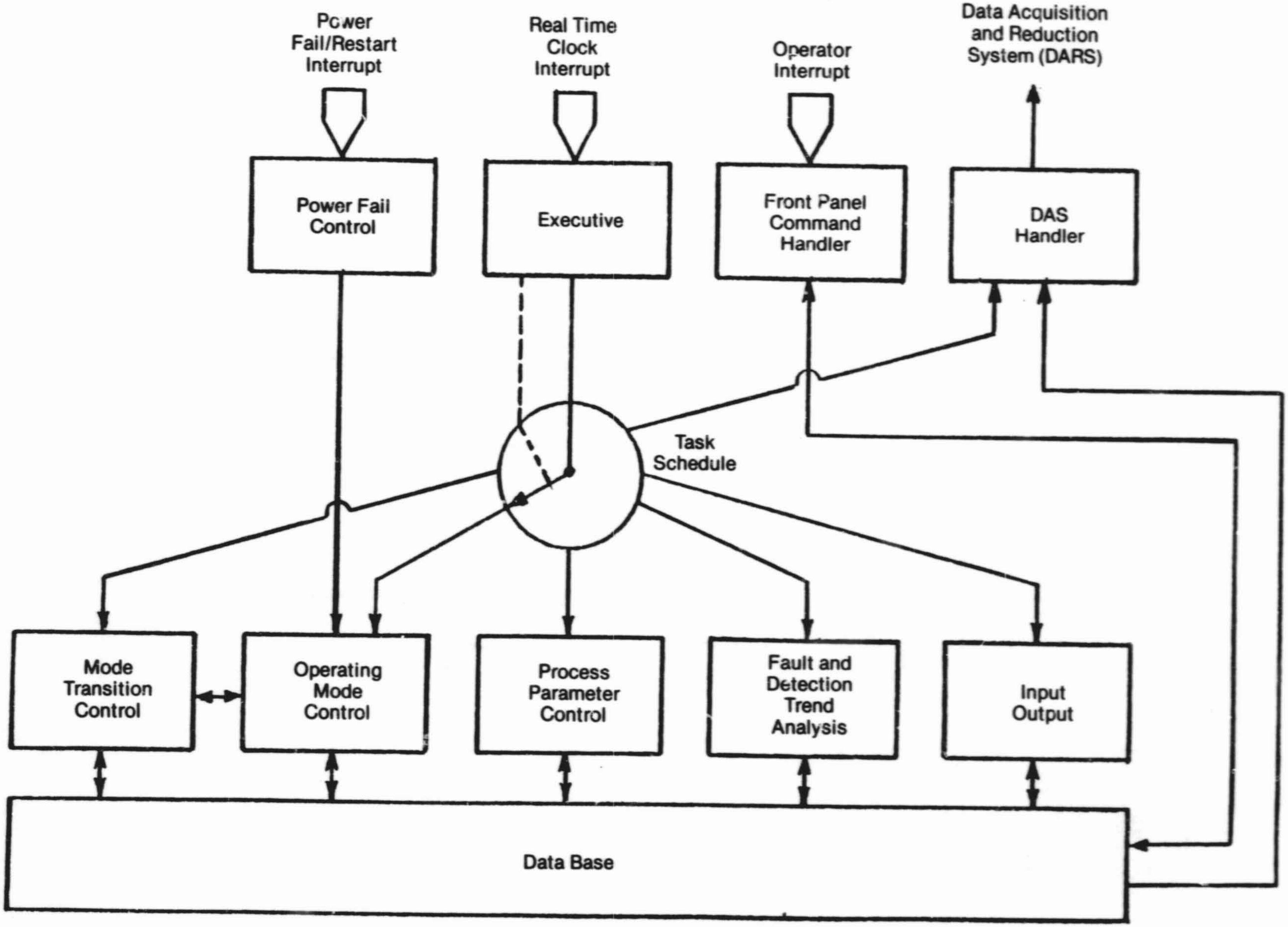

FIGURE 11 WS-1 C/M I SOFTWARE BLOCK DIAGRAM (LEVEL I)

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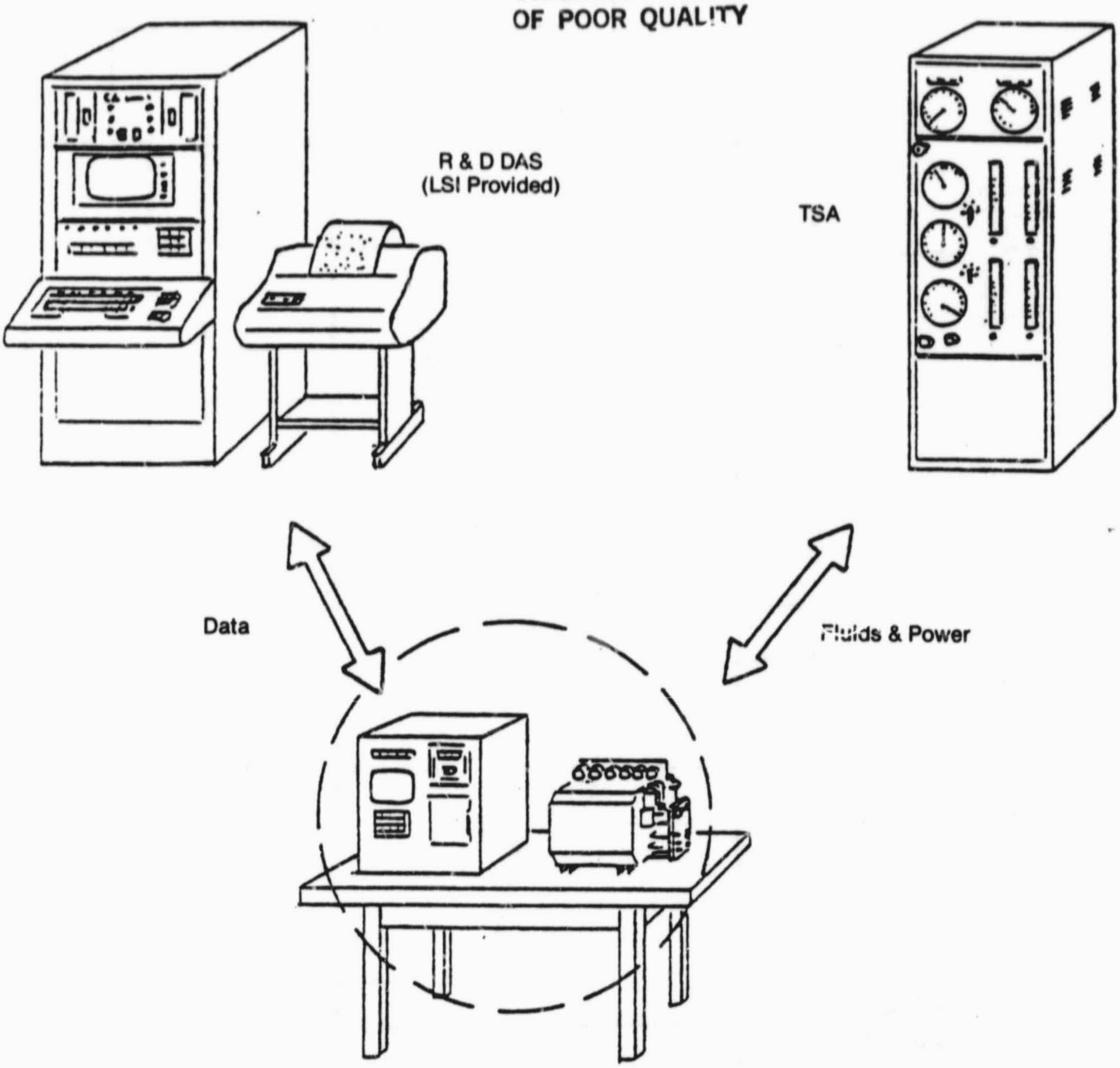


FIGURE 12 PROGRAM HARDWARE: WS-1 AND TSA

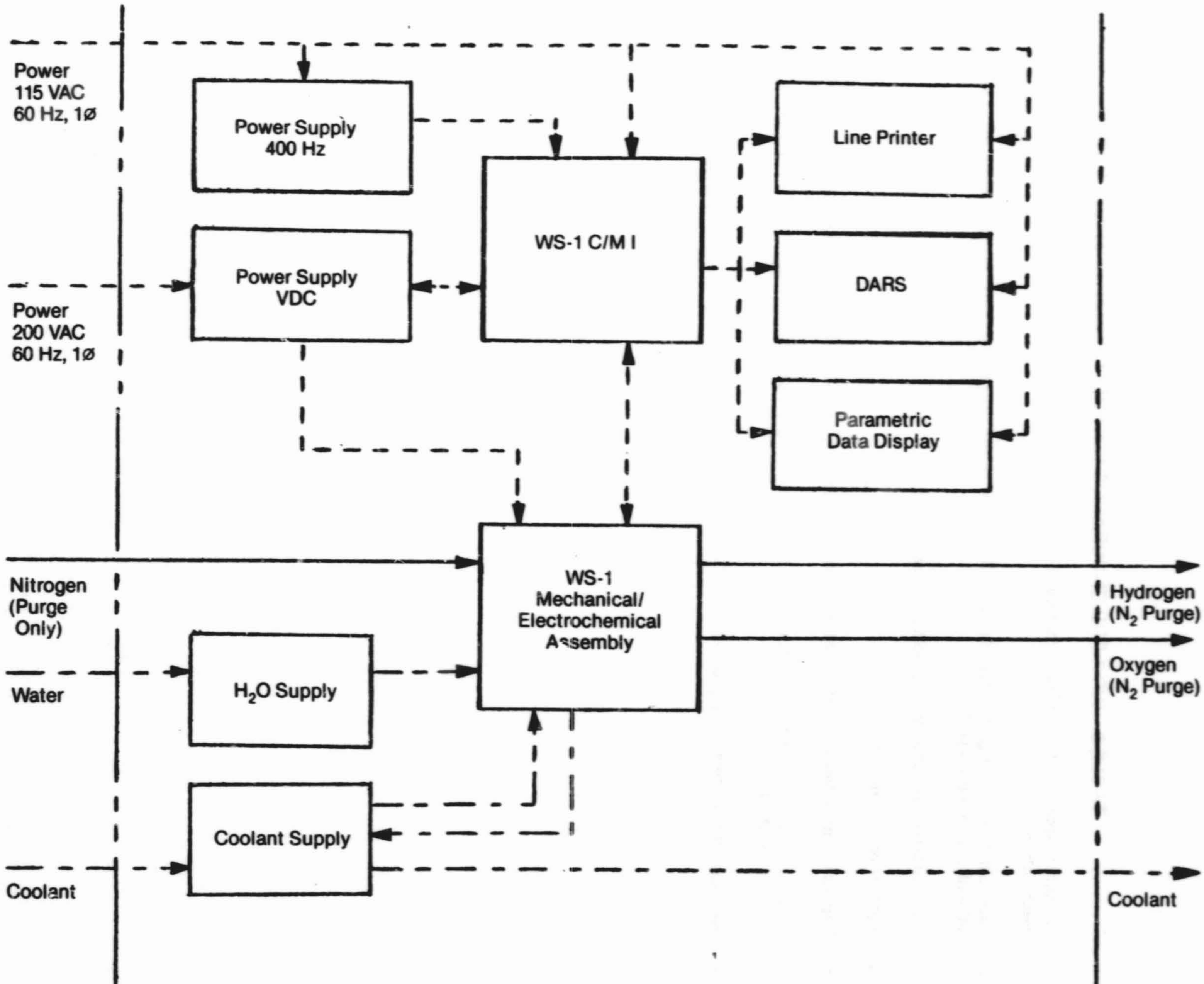


FIGURE 13 WS-1 SUBSYSTEM AS INTEGRATED WITH TEST SUPPORT ACCESSORIES

TABLE 6 WS-1 PRE-ENDURANCE TEST REFURBISHMENT ACTIVITIES

1. Visually inspected the 3-FPC valve seats, noting no deterioration, and replaced the ΔP and system pressure diaphragms.

2. Replaced the "O" rings in both the H_2 and O_2 subsystem purge solenoid valves to eliminate internal to external leaks within the valves.

3. Recalibrated the subsystem pressure transducers.

4. Recharged the module.

5. Replaced faulty relays (in the C/M I) controlling the Coolant Control Assembly diverter valve.

6. Modified the software to prevent current changes during a water fill, thereby maintaining constant gas flows through the 3-FPC.

7. Reloaded the software program into the C/M I.

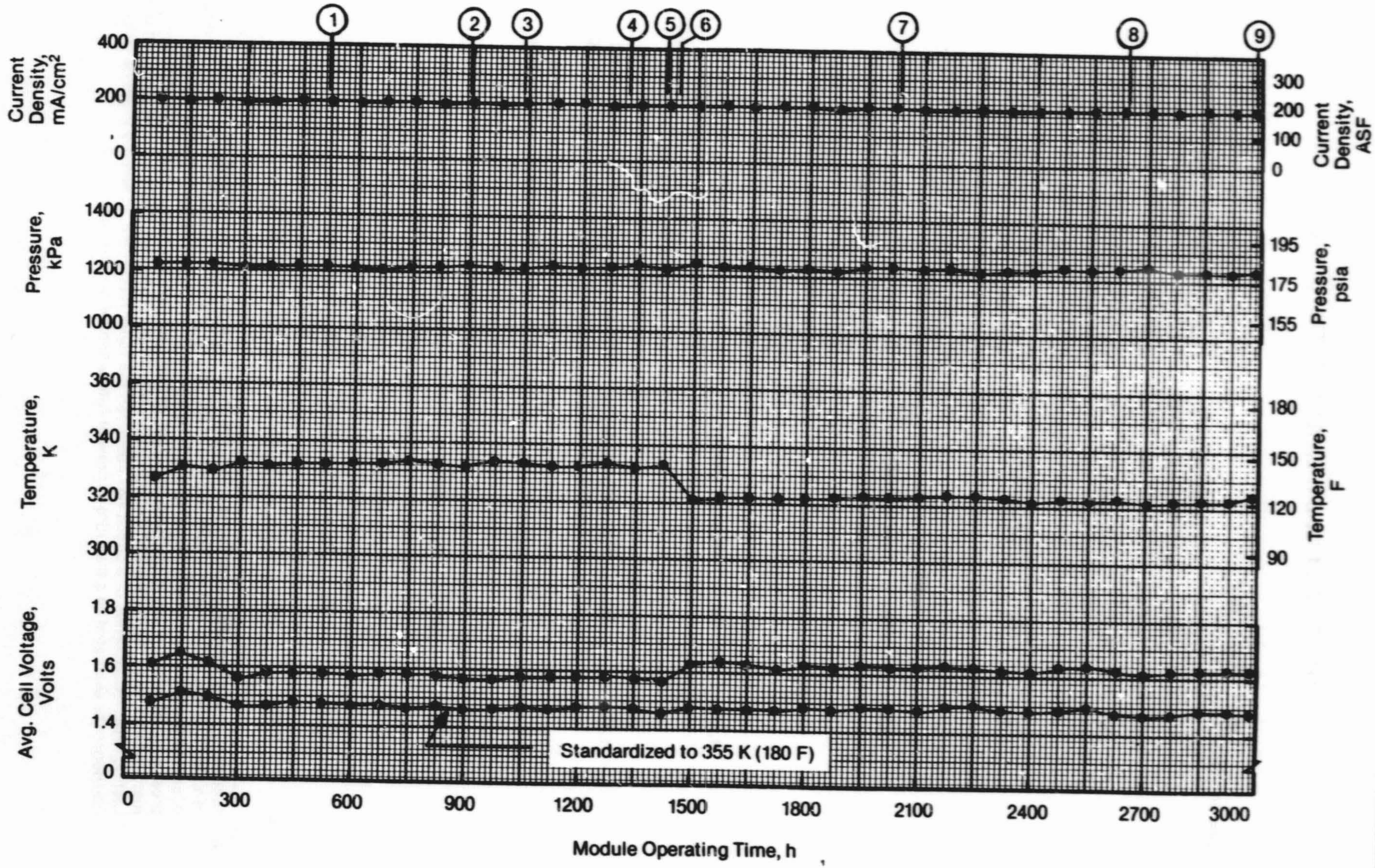


FIGURE 14 WS-1 MODULE PERFORMANCE

TABLE 7 WS-1 120-DAY ENDURANCE TEST SHUTDOWN LIST

Shutdown No.	Total Operating time, h	Continuous Operating time, h	Shutdown Symptom	Shutdown Cause/Action Taken	Down Time, d
1	520	520	Low system pressure	Premature wear of regulator diaphragm; diaphragm replaced and test resumed	0.1
2	880	360	None apparent	Computer shutdown due to software failure. Software anomaly not determined. Software reloaded and testing restarted.	3.0
3	1,038	158	None apparent	Computer CRT display inconsistent with actual parameter values. Recurrent software anomaly caused C/M I shutdown. Software set points modified, program reloaded and test restarted.	0.1
4	1,320	282	Error in C/M I Real Time Executive	Undetermined software anomaly caused failure of timely execution of software programs. The Supplementary Shutdown Controller (SSC) shut down the subsystem. C/M I circuit boards were replaced, the software was reloaded and testing was restarted.	0.5
5	1,415	95	High cell voltage	Unexpected deterioration of O-ring in H_2 regulator permitted excess gas flow. O-ring replaced with O-ring made of EPR. Module recharged and test restarted.	1.0
6	1,453	38	High cell voltages (Erroneous Signal)	Relays on the C/M I Fault Relay Board failed due to excessive wear, resulting in transmission of a "maximum voltage" signal for the cell voltages. The relays were replaced. A failed pico processor between the C/M I and the DARS was also discovered and replaced. Testing was restarted. [a]	17.0
7	2,028	575	None apparent	C/M I memory board failure caused SSC to shut down subsystem. The memory board was replaced, the program reloaded and testing restarted.	0.3
8	2,640	612	Power interruption	Building power failure. Software reloaded and testing restarted.	0.3
9	2,980	340		Completion of test	

a. At restart, it was noticed that SFWEM ΔPs were not acceptable. Disassembly of the module revealed damage to the cell matrices and cell housings. An evaluation indicated that during the relay board failure, the water feed solenoid opened. This caused an abrupt change in the differential pressures between the cell water feed, hydrogen and oxygen cavities, rupturing the gas separator matrices and resulting in localized damage to the cell frames. The spare WEM was installed and the testing resumed. Addition of a check valve between the water feed solenoid and the water deionizer cartridge was evaluated as a measure to prevent future similar occurrences.

Conclusions

The WS-1 endurance test results verified WS-1 subsystem performance and reliability. Module operating voltages remained constant, and after 124 days, subsystem components exhibited no major deficiencies or life-limiting characteristics. Wear experienced on components was as expected for subsystem operating conditions, with the exception of unanticipated deterioration experienced on one H_2 regulator diaphragm and one O-ring (shutdown Nos. 1 and 5). These were isolated, premature part failures and were not considered to be indicative of overall M/E A performance, capability or limitations. Other shutdowns, as noted, were C/M I related. It is concluded, therefore, that the evaluation demonstrated successful performance and reliability characteristics of the WS-1 and provides a strong basis for subsequent development of a preprototype-level subsystem.

IMPROVED THREE-FLUID PRESSURE CONTROLLER ENDURANCE TEST

Two improved 3-FPC units were fabricated and assembled during the previous contractual effort. One unit was installed on the WS-1 subsystem and the other unit was used for independent evaluation. This chapter discusses the results of extended endurance testing of the independent evaluation unit.

Background

The previously developed improved 3-FPC is shown pictorially in Figure 15 and schematically in Figure 16. The 3-FPC was developed to meet the unique fluid and pressure control requirements of a SFWEM. It controls and monitors fluid levels and differentials during all operating modes, including both steady-state and cyclic operation and startups and shutdowns. The 3-FPC includes three pressure transducers (one absolute, two differential), three pressure regulators, three Regulator Position Indicators (RPI), four electric heaters (wired in parallel) and a thermistor in a single unit. The physical characteristics and operating conditions are shown in Table 8.

Functionally, the 3-FPC pressurizes the feed water and product H_2 and O_2 of the SFWES. During startup and shutdown, the subsystem pressure is ramped between ambient and operating levels. At all times, the differential pressure between H_2 and O_2 streams and the water feed stream are controlled to ensure proper subsystem performance. Pressures are sensed by internal pressure transducers and controlled by motor-driven regulators. The 3-FPC is internally heated to prevent condensation from occurring.

A test stand was developed for the characterization and endurance testing of the 3-FPC. The test stand enables operation of the 3-FPC under various simulated OGS operating modes and conditions. The test stand is shown pictorially in Figure 17 and schematically in Figure 18. High pressure bottled air, compressed air or N_2 can be used to simulate the flow of O_2 through the 3-FPC; high pressure H_2, N_2 or air can be used to simulate the flow of H_2 through the 3-FPC. The test stand includes a 3-FPC electronic Controller, shown in the center of Figure 17. This electronic Controller simulates the 3-FPC control portion of an OGS C/M I. The front panel of the electronic Controller provides readouts of the three pressures and adjustments of the pressure control set points. An Actuator Exerciser, shown in the upper right corner of Figure 17, was developed to simulate OGS operating mode changes. The Actuator Exerciser controls the opening and closing of solenoid valves on the test stand in a timed sequence and simulates the shutdown, standby, normal, purge and water fill portions of OGS operation.

Test Program

Over 1,200 hours of parametric and endurance testing were accumulated on the improved 3-FPC during the previous contractual effort. The current test program, an extended endurance test, consisted of cycles of simulated startup, operation at constant pressure, simulated shutdown (pressure decay) and water fill cycles. An evaluation was made of the controller's capability to maintain constant pressure differentials at varying system reference pressures. A typical test cycle for the 3-FPC endurance testing is shown in Figure 19.

Pre-Endurance Test Activities

The following activities were completed prior to initiation of the extended endurance testing. A heater circuit was added to the 3-FPC electronic controller to provide for heating of the 3-FPC mechanical assembly, thus simulating operation with a WS-1 subsystem. The 3-FPC adjusting threads, diaphragms, O-rings and drive pins were inspected and were found to be in good condition, showing no signs of wear following the previous contractual test activities.

Endurance Test

The endurance testing consisted of repeatedly cycling the 3-FPC through pressurization, operation at pressure, depressurization and simulated shutdown, as previously shown in Figure 19. A 70-minute total operating cycle (consisting of 20 minutes of pressurization, 20 minutes of operation at pressure, 20 minutes of depressurization and 10 minutes of

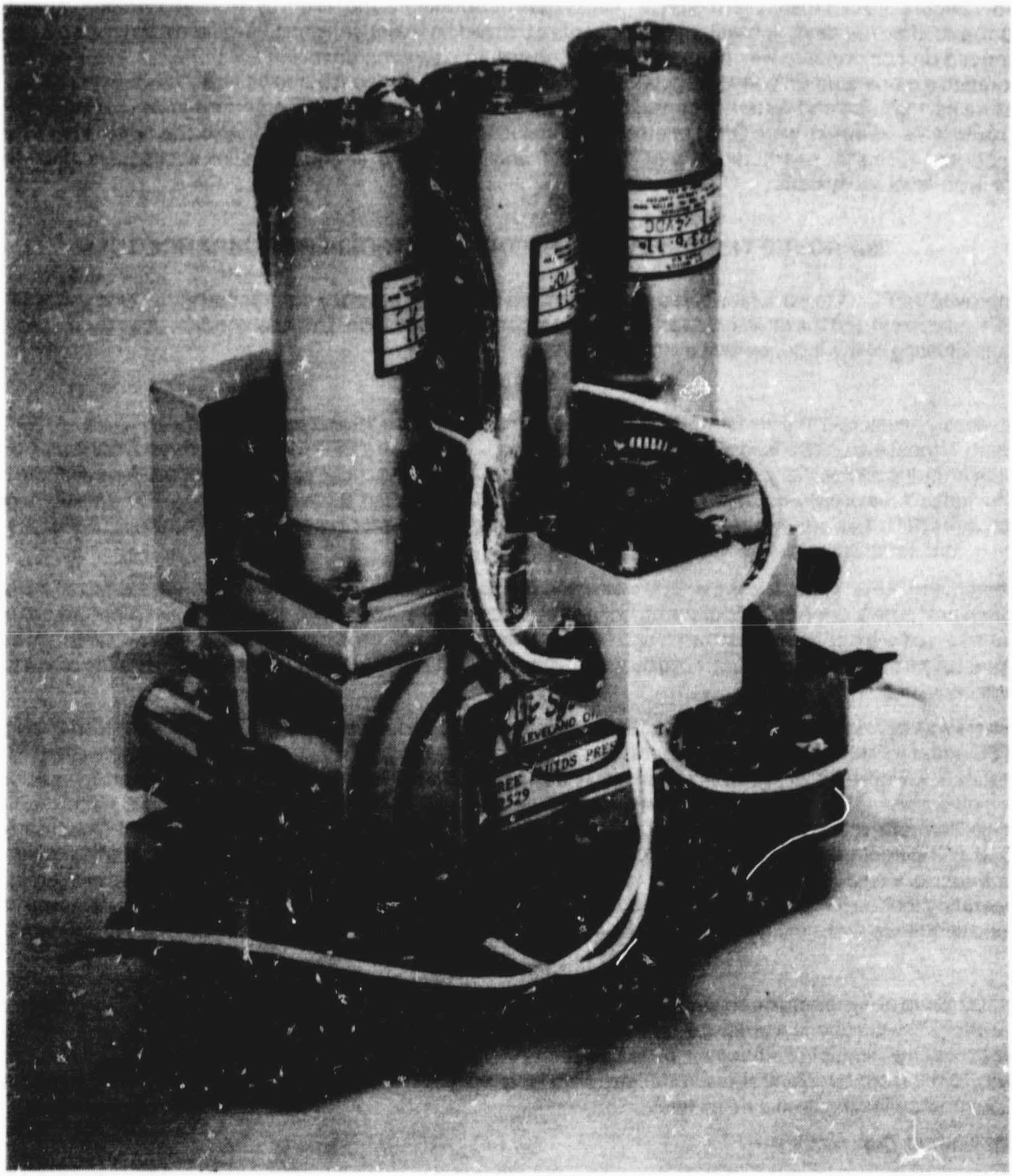


FIGURE 15 THREE-FLUID PRESSURE CONTROLLER

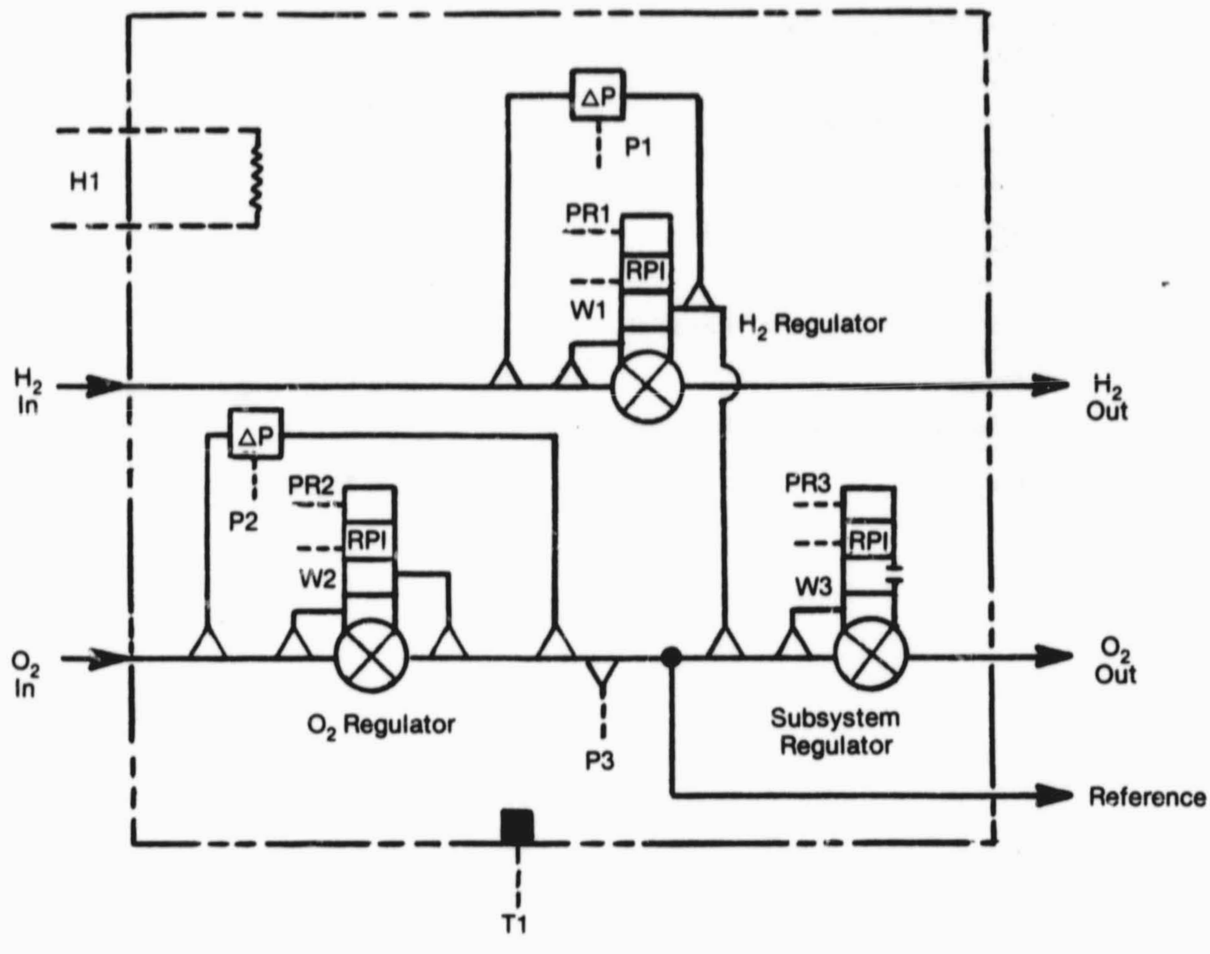


FIGURE 16 THREE-FLUID PRESSURE CONTROLLER MECHANICAL SCHEMATIC

TABLE 6 THREE-FLUID PRESSURE CONTROLLER PHYSICAL CHARACTERISTICS AND OPERATING CONDITIONS

Physical Characteristics	
Weight, kg (lb)	4.9 (10.7)
Volume, cm^3 (in^3)	613 (95)
Configuration, cm (in)	17.8 x 12.7 x 6.9 (7.0 x 5.0 x 2.7)
Operating Conditions	
H_2 Flow Rate, kg/d (lb/d)	
Nominal	0.10 (0.23)
Range	0.06 to 0.40 (0.13 to 0.88)
O_2 Flow Rate, kg/d (lb/d)	
Nominal	0.84 (1.84)
Range	0.45 to 3.18 (1.0 to 7.0)
Subsystem Pressure, kPa (psia)	
Nominal	1,241 (180)
Range	103 to 1,482 (0 to 200)
H_2 to Subsystem Pressure, kPa (psid)	
Nominal	14 (2.0)
Range	11 to 17 (1.6 to 2.4)
O_2 to Subsystem Pressure, kPa (psid)	
Nominal	28 (4.0)
Range	25 to 30 (3.6 to 4.4)

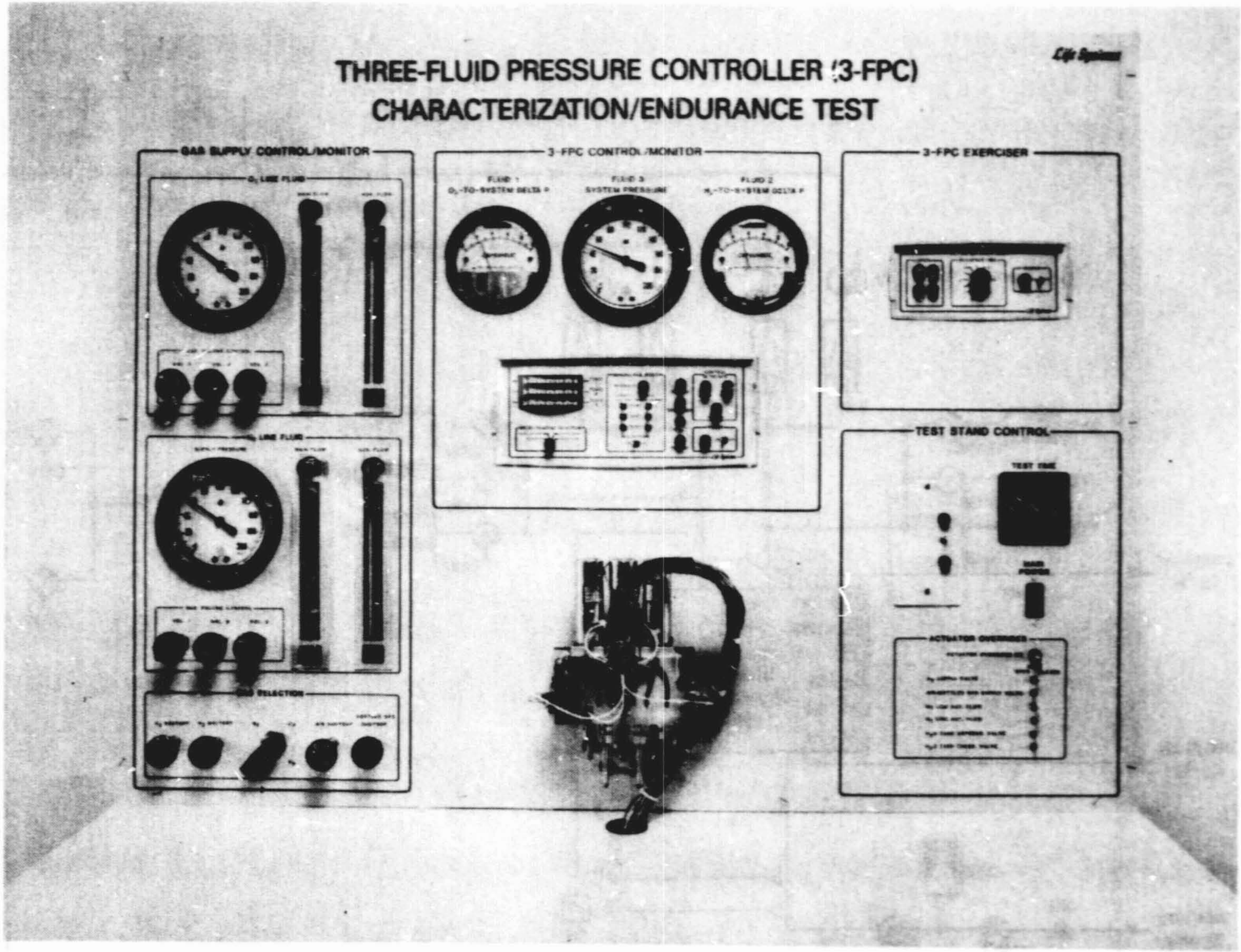


FIGURE 17 THREE-FLUID PRESSURE CONTROLLER TEST STAND

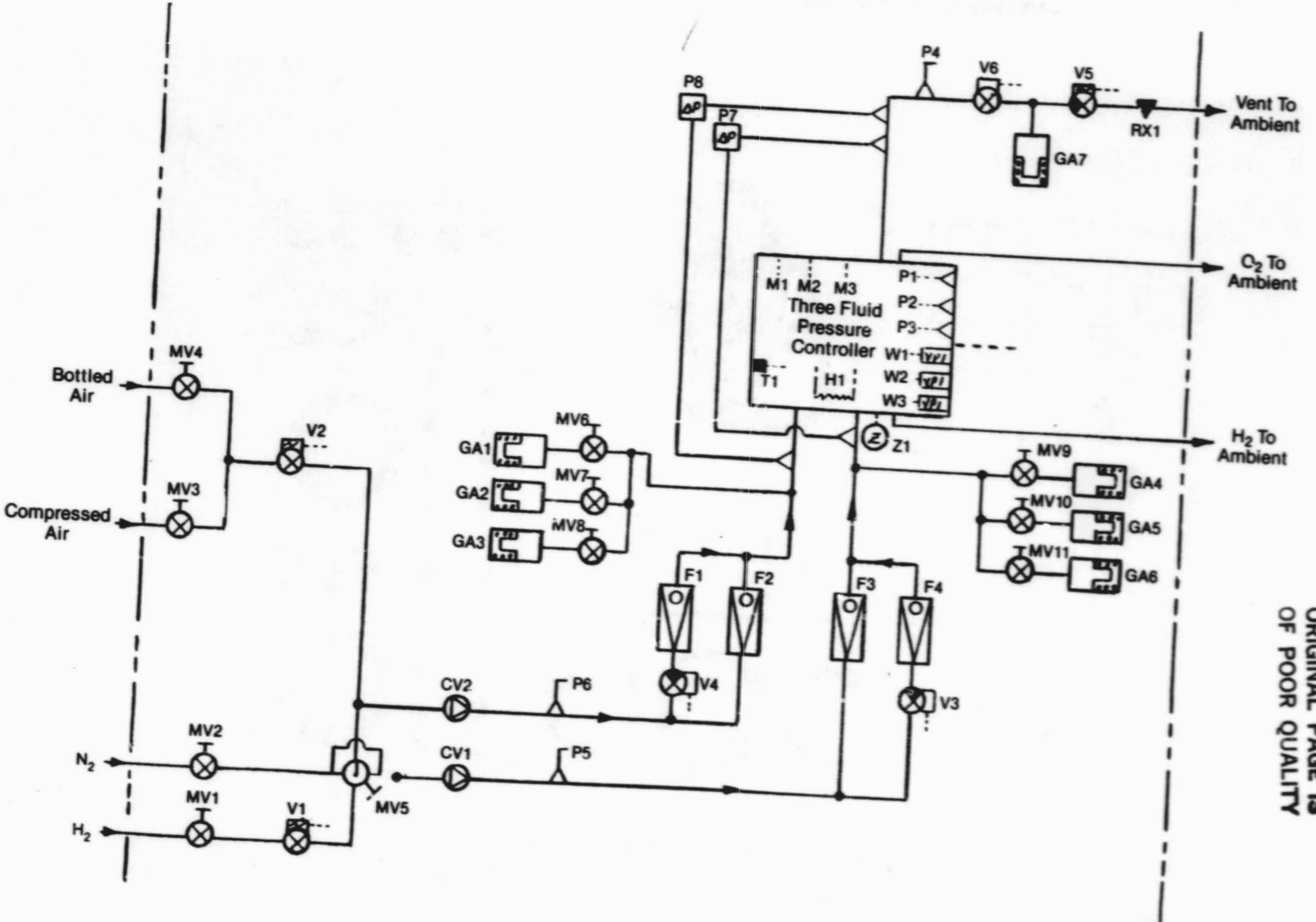
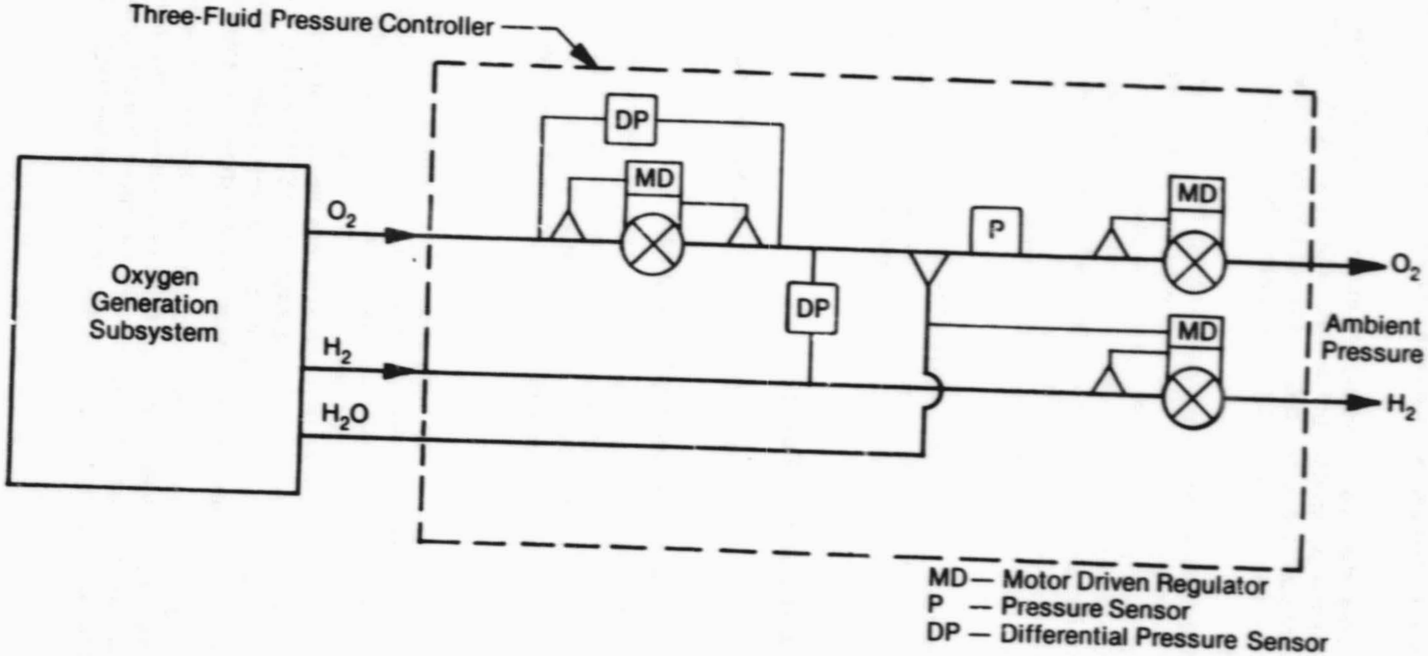


FIGURE 18 THREE-FLUID PRESSURE CONTROLLER TEST STAND MECHANICAL SCHEMATIC



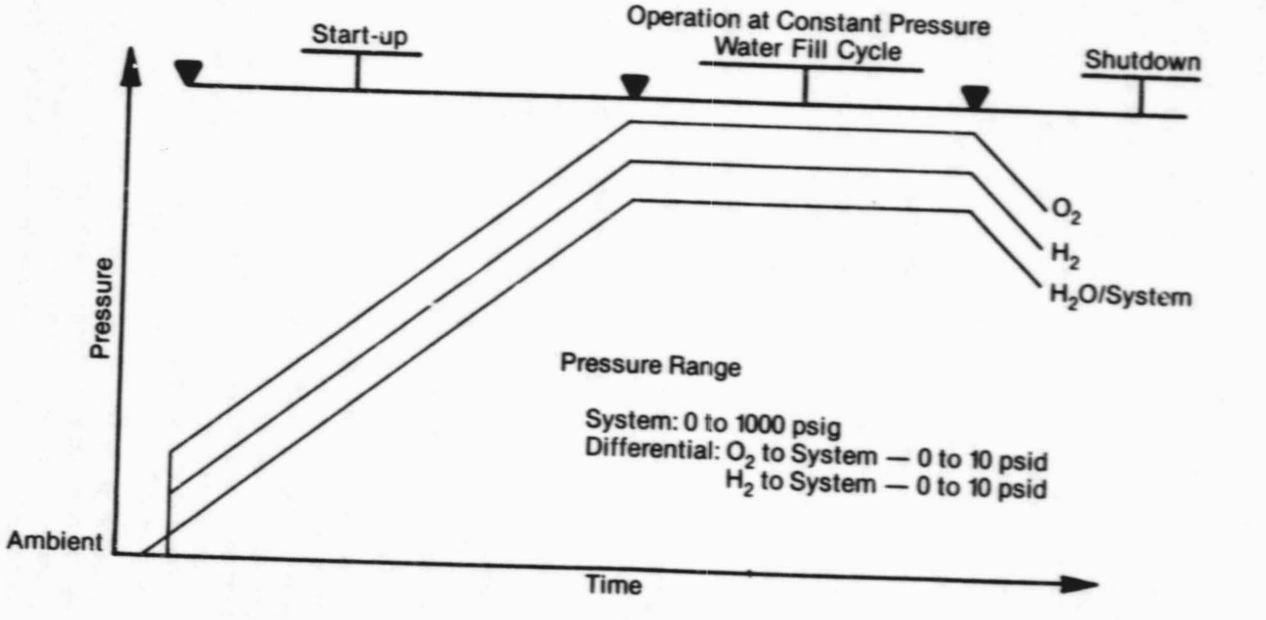


FIGURE 19 PRESSURE CONTROLLER TYPICAL TEST CYCLE

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simulated shutdown) was selected for the endurance test. Three typical cycles are shown in Figure 20. Compressed air was utilized as the test gases in place of commercial bottled H_2 and N_2, thus avoiding frequent and costly replacement of gas cylinders.

The 3-FPC was evaluated for 8,650 hours (7,405 pressurization/depressurization cycles). The endurance test data, shown in Figure 21, was accumulated at random time intervals and at random points in the pressurization/depressurization cycle to verify stability of control of the 3-FPC regulators. For this test program, the system pressure varied between a lower limit of 101 kPa (14.7 psia) and an upper limit of 515 kPa (75 psia). It can be seen that the 3-FPC regulators effectively maintained stable H_2-to-System and O_2-to-System differential pressures.

Two shutdowns occurred during the endurance testing. The first shutdown, which was voluntarily initiated, occurred approximately 3,100 hrs into the test. At that time, the original 3-FPC valve seats were replaced with valve seats made from a material exhibiting better cold flow characteristics at WS-1 operating temperatures. The second shutdown, occurring approximately 4,300 hrs into the test, was the result of a premature failure of the 3-FPC electronic controller power supply. During this shutdown, it was noted that the gasket material in the 3-FPC plunger housing assembly had moved from underneath its retention washer. The gasket and washer were realigned during this shutdown. The slight perturbation in the differential pressure data at the 5,700-hr point was due to adjustments made in the 3-FPC electronic controller.

Conclusions and Recommendations

On the basis of the extended endurance test data, the 3-FPC has been shown to be a viable and reliable device for the control of SFWES gas pressures. Suggestions for modification to improve future 3-FPCs include removal of excess body material to minimize weight and volume and relocation of the differential pressure transducers to the top of the unit from the current installation location on the ends of the unit.

TECHNOLOGY ADVANCEMENT STUDIES

Further improvements in subsystem simplification and reliability through component development and modification are discussed in the following sections.

Water Electrolysis Subsystem Fluid Control Assembly Development

Control and monitoring of the flow of water, H_2, N_2 and O_2 in a SFWES during steady-state operation and intermode transitions is currently performed by fourteen (14) discrete components. These function can now be accomplished by an integrated unit, the Water Electrolysis Subsystem Fluid Control Assembly (WES FCA), which weights only 4.1 kg (9.0 lbs) and occupies only 2,600 cm^3 (159 in^3). The relationship of these integrated components with respect to an O_2 generation subsystem is shown schematically in Figure 22.

Design

The WES FCA, shown schematically in Figure 23 and pictorially in Figure 24, is an integration of shutoff valves, check valves, filters and sensors combined into a single, light-weight motor-actuated Line Replaceable Unit (LRU). This LRU replaces seven (7) two-way valves, three (3) orifices, two (2) check valves, one (1) differential pressure transducer, one (1) absolute pressure transducer and includes four (4) filters. Figure 25 shows a disassembled view of the WES FCA. The WES FCA controls and filters the supply of through the subsystem and monitors the differential pressure across the water storage tank. The unit also filters and controls the supply of N_2 for purging H_2 and O_2 from associated passages in the SFWEM. All functions are controlled by a computerized process controller. The design objectives and the operating characteristics and conditions are given in Tables 9 and 10, respectively. The functions and advantages of this integrated unit are shown in Table 11.

Actuation of the FCA valves is provided for by a motorized drive system with visual and electronic position indicators. A manual override and C/M I backup power, i.e., batteries, are provided to enable actuation of the valves during loss of primary power. Filters protect specific valves from contaminants and are placed upstream in the flow to the valves. The valve position combinations are limited to those required for SFWES operation. The mode transitions and permitted valve combinations are shown in Table 12.

Test Support Accessories Development

Test Stand. A test stand was specifically fabricated for the WES FCA, both to characterize its performance and demonstrate endurance. The test stand is shown in Figure 26 with the WES FCA mounted in place. The test stand mechanical schematic is shown in Figure 27. Water, N_2 and O_2 are provided so that characterization testing may proceed under normal operating conditions.

WES FCA Controller. An electronic Controller was designed and fabricated to monitor and control the sensors and actuators of the WES FCA. The Controller is shown in the center of Figure 26 and, along with the WES FCA, in Figure 28. The Controller is a microprocessor-based unit which simulates the functions of a subsystem C/M I package.

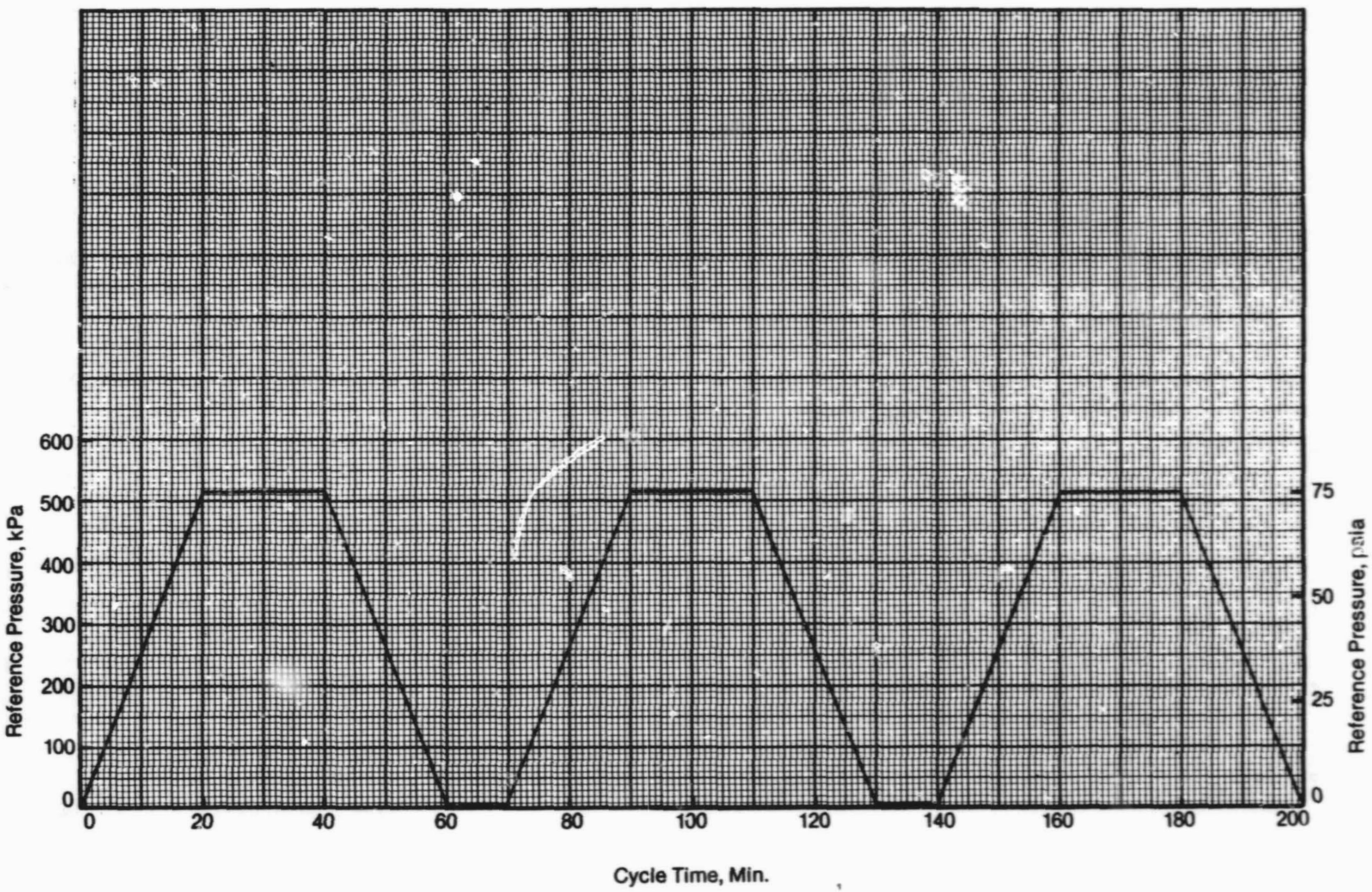

FIGURE 20 3-FPC ENDURANCE TEST OPERATING CYCLE

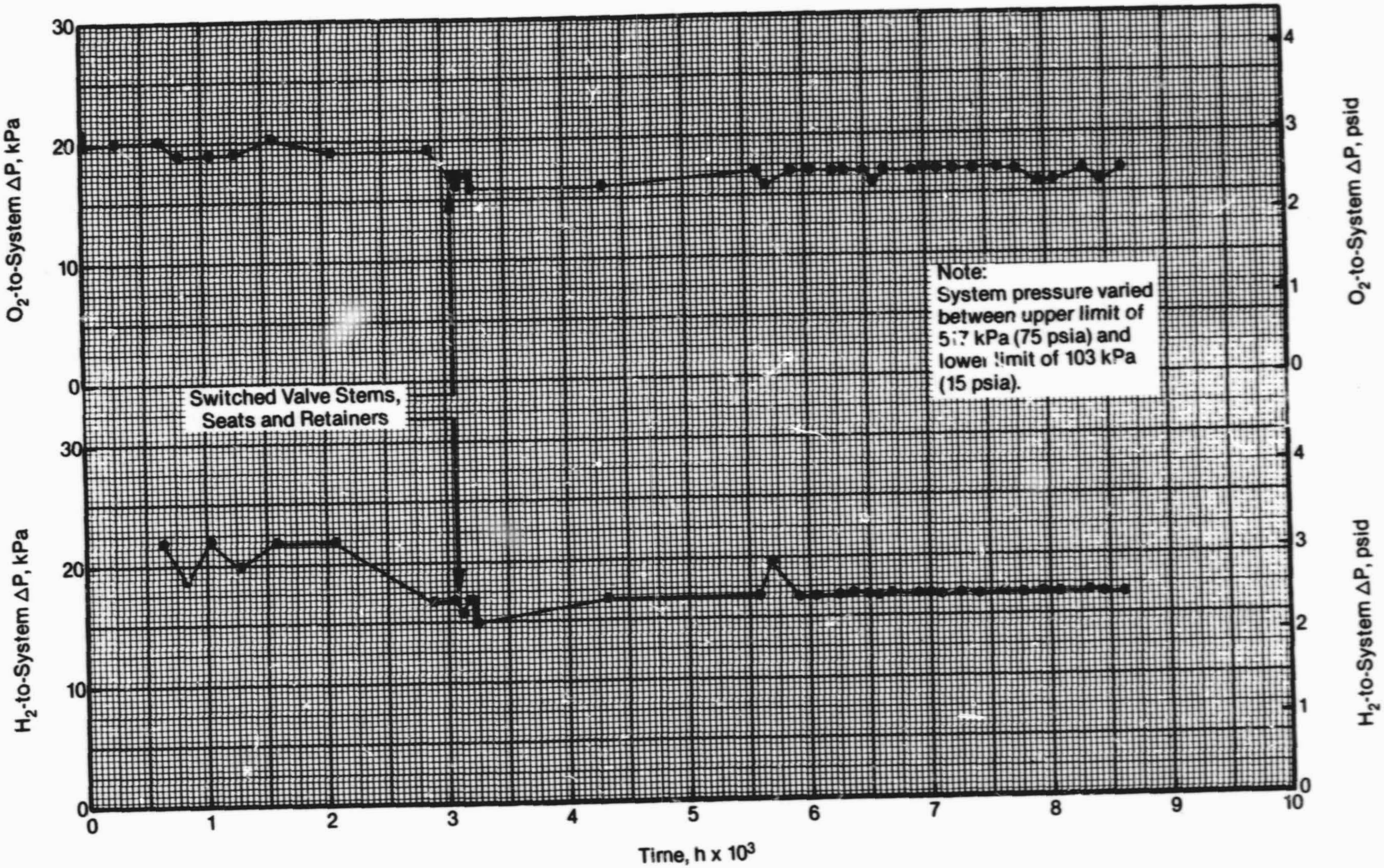

FIGURE 21 3-FPC EXTENDED ENDURANCE TESTING

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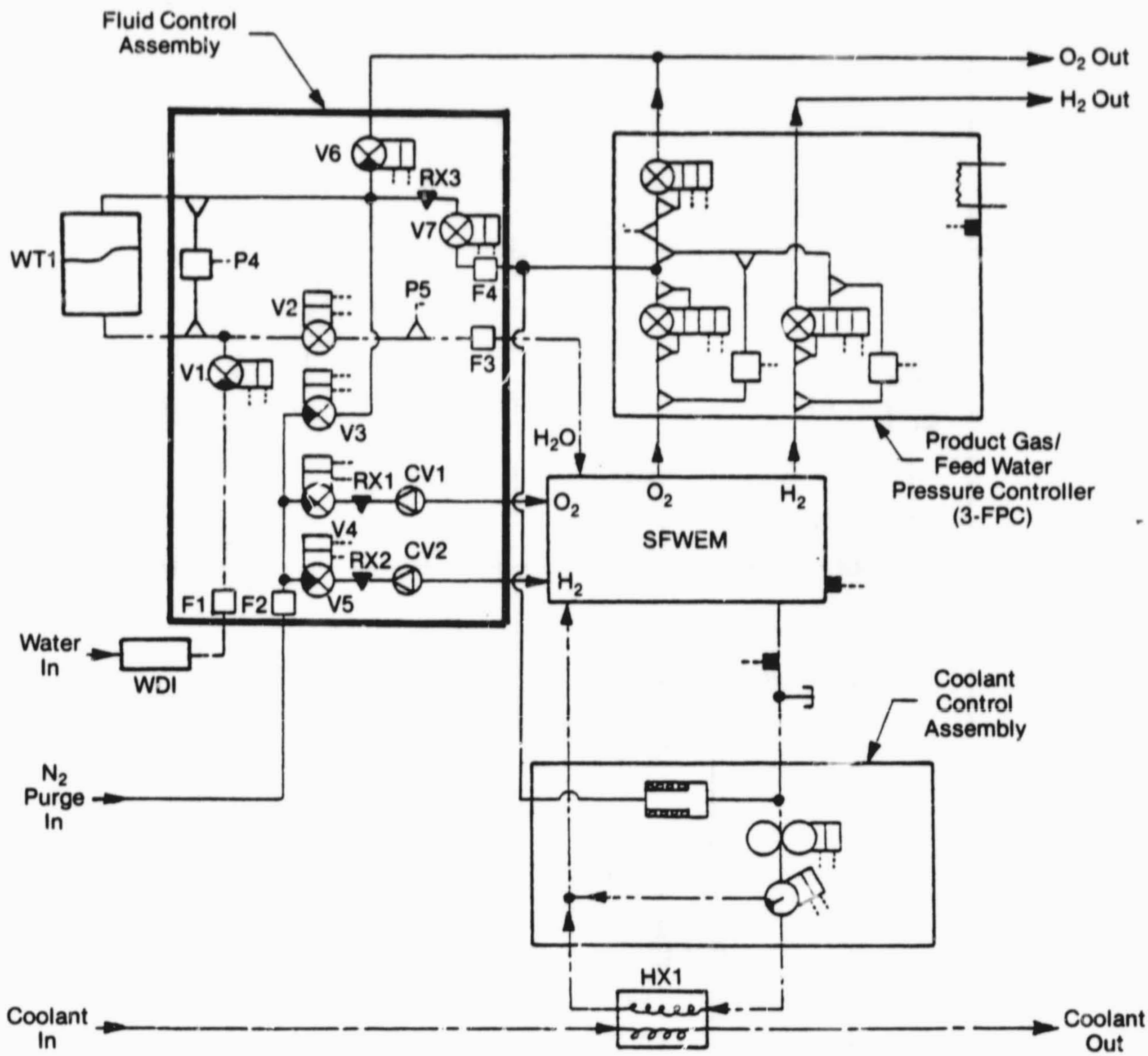

FIGURE 22 OGS SHOWING FLUID CONTROL ASSEMBLY COMPONENTS

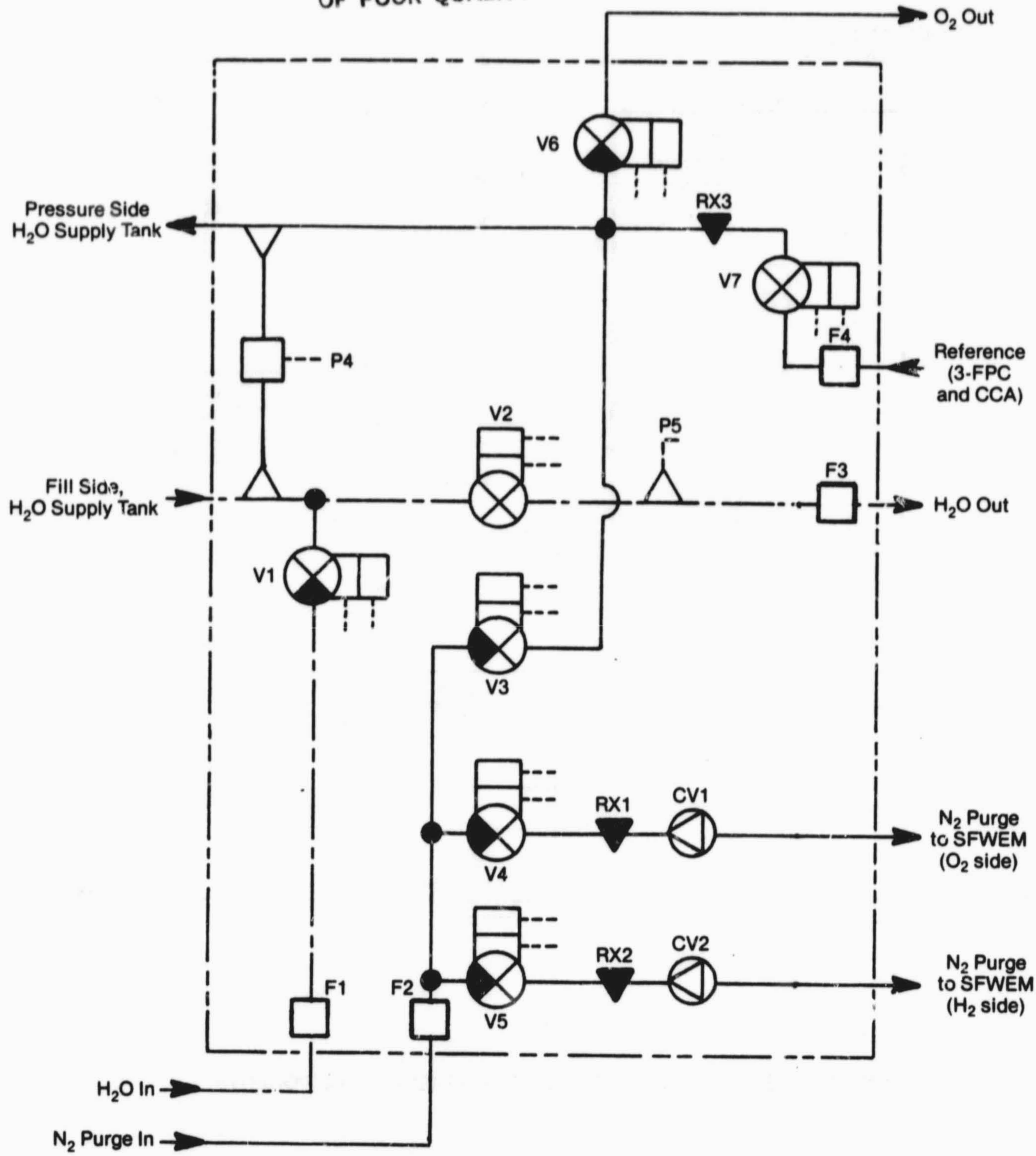

FIGURE 23 WES FLUID CONTROL ASSEMBLY SCHEMATIC

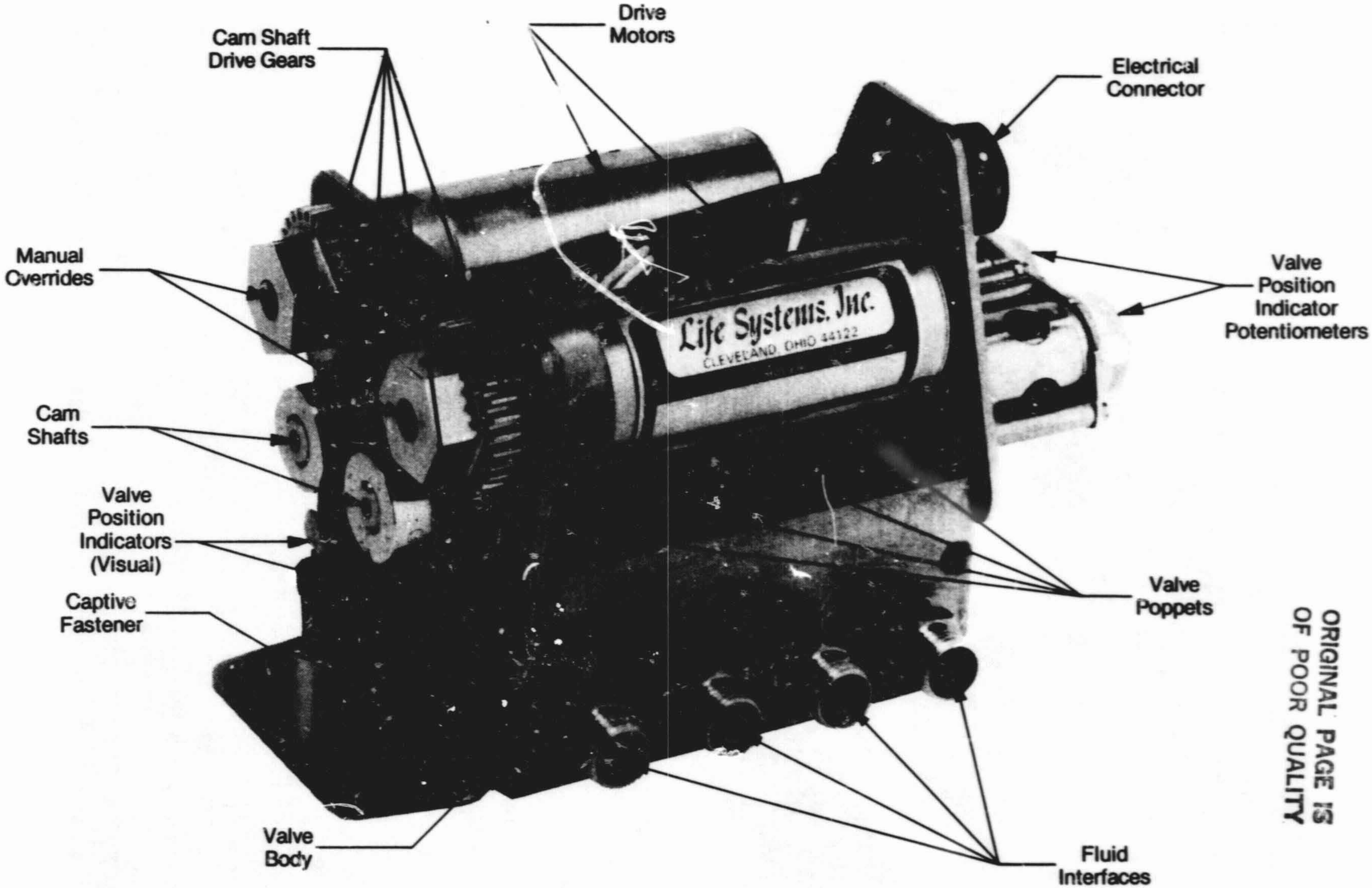

FIGURE 24 WATER ELECTROLYSIS SUBSYSTEM FLUIDS CONTROL ASSEMBLY

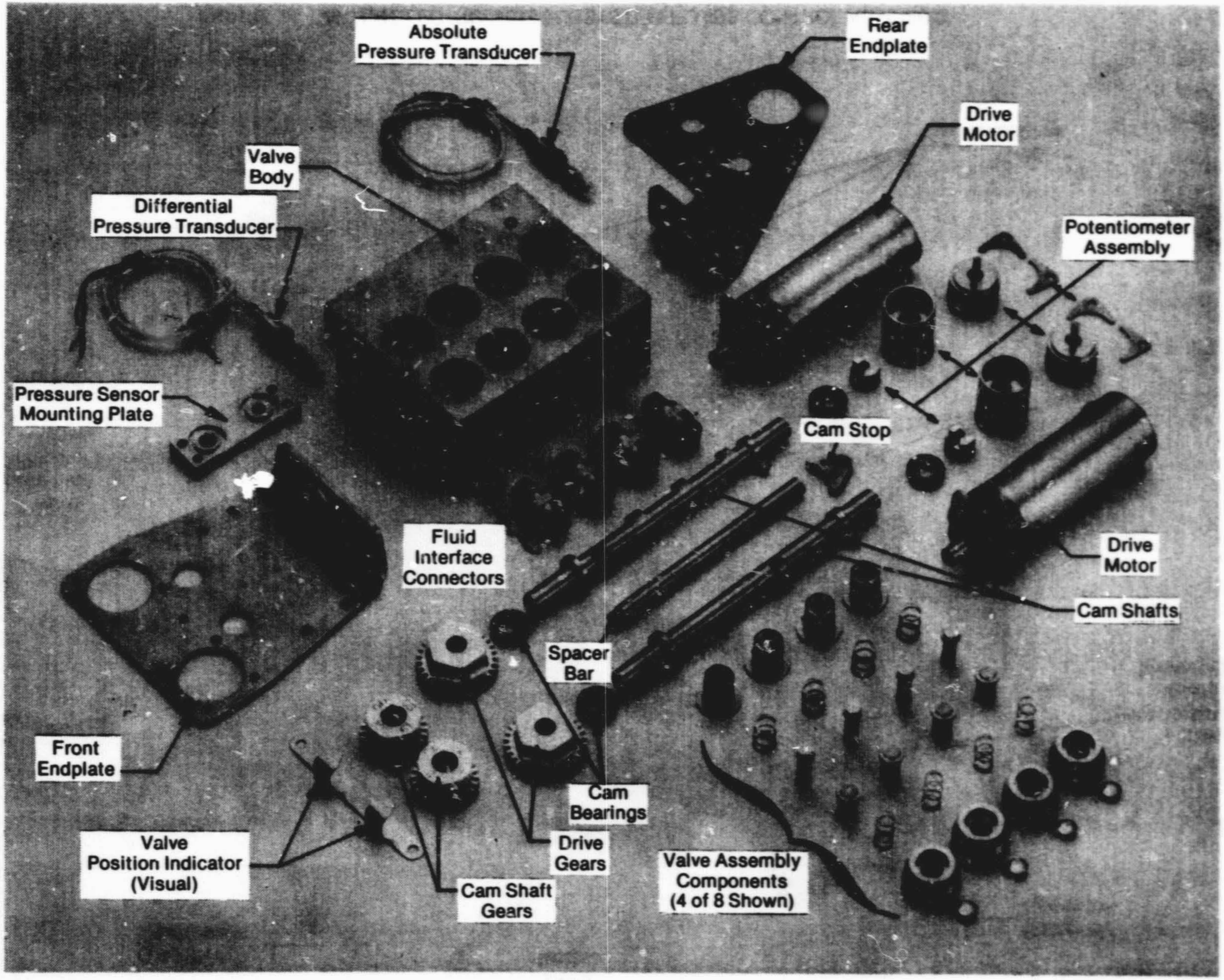

FIGURE 25 WATER ELECTROLYSIS FLUIDS CONTROL ASSEMBLY — EXPLODED VIEW

TABLE 9 WES FLUID CONTROL ASSEMBLY DESIGN OBJECTIVES

- Combine into a single unit the following components:
  - Seven two-way valves
  - One differential pressure transducer
  - One absolute pressure transducer
  - Three orifices
  - Two check valves
  - Four filters
- Line Replaceable Unit
- Weight, 4.1 kg (9.0 lb)
- Volume, 2,600 cm^3 (159 in^3)
- Reduce subsystem complexity
- Implement Line Replaceable Unit (LRU)-type mounting and fluid connections

TABLE 10 WES FLUID CONTROL ASSEMBLY OPERATING CHARACTERISTICS AND CONDITIONS

Operating Interfaces	Nominal Point	Nominal Range
N_2 Purge		
- Supply		
Pressure, kPa (psig)	1,205 (160)	101-2,170 (0-300)
Temperature, K (F)	294 (70)	283-311 (50-200)
Flow, scc/min	200	0-1,000
- Out H_2		
Pressure, kPa (psig)	1,205 (160)	101-2,170 (0-300)
Temperature, K (F)	333 (140)	283-311 (50-200)
Flow, scc/min	100	0-500
- Out O_2		
Pressure, kPa (psig)	1,205 (160)	101-2,170 (0-300)
Temperature, K (F)	333 (140)	283-311 (50-200)
Flow, scc/min	100	0-500
Water		
- Supply		
Pressure, kPa (psig)	239 (20)	101-515 (0-60)
Temperature, K (F)	294 (70)	283-311 (50-200)
Flow, scc/min	600	0-1,500
- Water Tank		
Pressure, kPa (psig)	1,205 (160)	101-2,170 (0-300)
Temperature, K (F)	322 (120)	283-311 (50-200)
Flow, Tank Fill/Normal Op., scc/min	600/5	0-1,500
- SFWEM H_2O Feed		
Pressure, kPa (psig)	1,205 (160)	101-2,170 (0-300)
Temperature, K (F)	322 (120)	283-311 (50-200)
Flow, scc/min	5	0-10
Reference Pressure		
- Water Tank		
Pressure, kPa (psig)	1,205 (160)	101-2,170 (0-300)
Temperature, K (F)	333 (140)	283-311 (50-200)
Flow, scc/min	5	0-15,000
- 3-FPC/CCA		
Pressure, kPa (psig)	1,205 (160)	101-2,170 (0-300)
Temperature, K (F)	333 (140)	283-311 (50-200)
Flow, scc/min	Approx. 0	0-10
Vent O_2/N_2		
Pressure, kPa (psig)	101 (0)	101-239 (0-20)
Temperature, K (F)	294 (70)	283-311 (50-200)
Flow, scc/min	0	0-15,000

TABLE 11 WES FLUID CONTROL ASSEMBLY FUNCTIONS AND ADVANTAGES

Functions

- Monitors and controls flow of H_2 and O_2 in a SFWES
- Controls and filters supply of N_2 for purging H_2 and O_2 from the SFWEM
- Controls and filters supply of water to the subsystem
- Monitors water differential pressure across the water storage tank

Size Reduction Factor

Size Factor	% Reduction	From	To
• No. of Components	93	14	1
• No. of Connections	70	30	9
• Weight, kg (lb)	22	5.2 (11.4)	4.1 (9.0)
• Volume, cm^3 (in^3)	60	6,555 (400)	2,600 (159)
• Power, W	92	24	2

Other Major Benefits

- Subsystem simplification for user acceptance
- Ease of in-flight maintenance (one Line Replaceable Unit)
- Applicable wherever WES technology is employed

TABLE 12 WES FCA MODE TRANSITIONS/VALVE COMBINATIONS SUMMARY

Legal Mode Transitions

A→B Normal to Shutdown

A→E Normal to Standby

B→A Shutdown to Normal

B→C Shutdown to Purge

B→E Shutdown to Standby

C→B Purge to Shutdown

D→B Unpowered to Shutdown

E→A Standby to Normal

E→B Standby to Shutdown

where: A = Normal B = Shutdown C = Purge
D = Unpowered E = Standby

Permitted Valve Combinations

Each of 7 valves has two possible states, open (O) and closed (C), giving $2^7 = 128$ combinations. Of these, 7 are used. These are labeled below:

V1	V2	V3	V4	V5	V6	V7
C	O	C	C	C	C	O
Normal, Shutdown						
C	C	C	C	C	C	C
Isolate, Stop Fill, Stop Pressurization						
C	C	C	C	C	O	C
Depressurize						
O	C	C	C	C	O	C
Water Fill						
C	C	O	C	C	C	C
Repressurize						
C	C	C	C	C	C	O
Pressure Adjustment						
C	O	C	O	O	C	O
Standby, Purge, Unpowered						

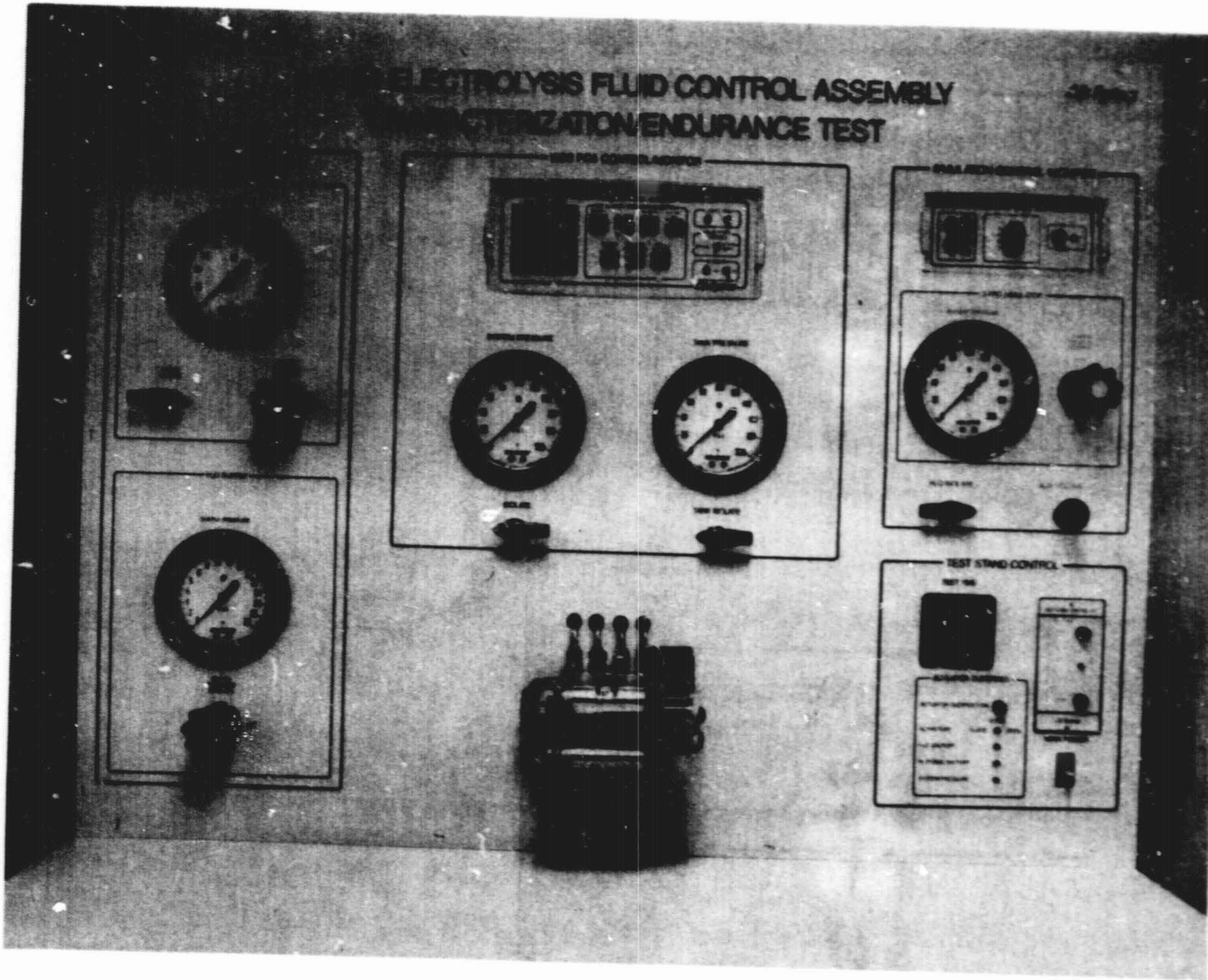

FIGURE 26 WES FCA TEST STAND

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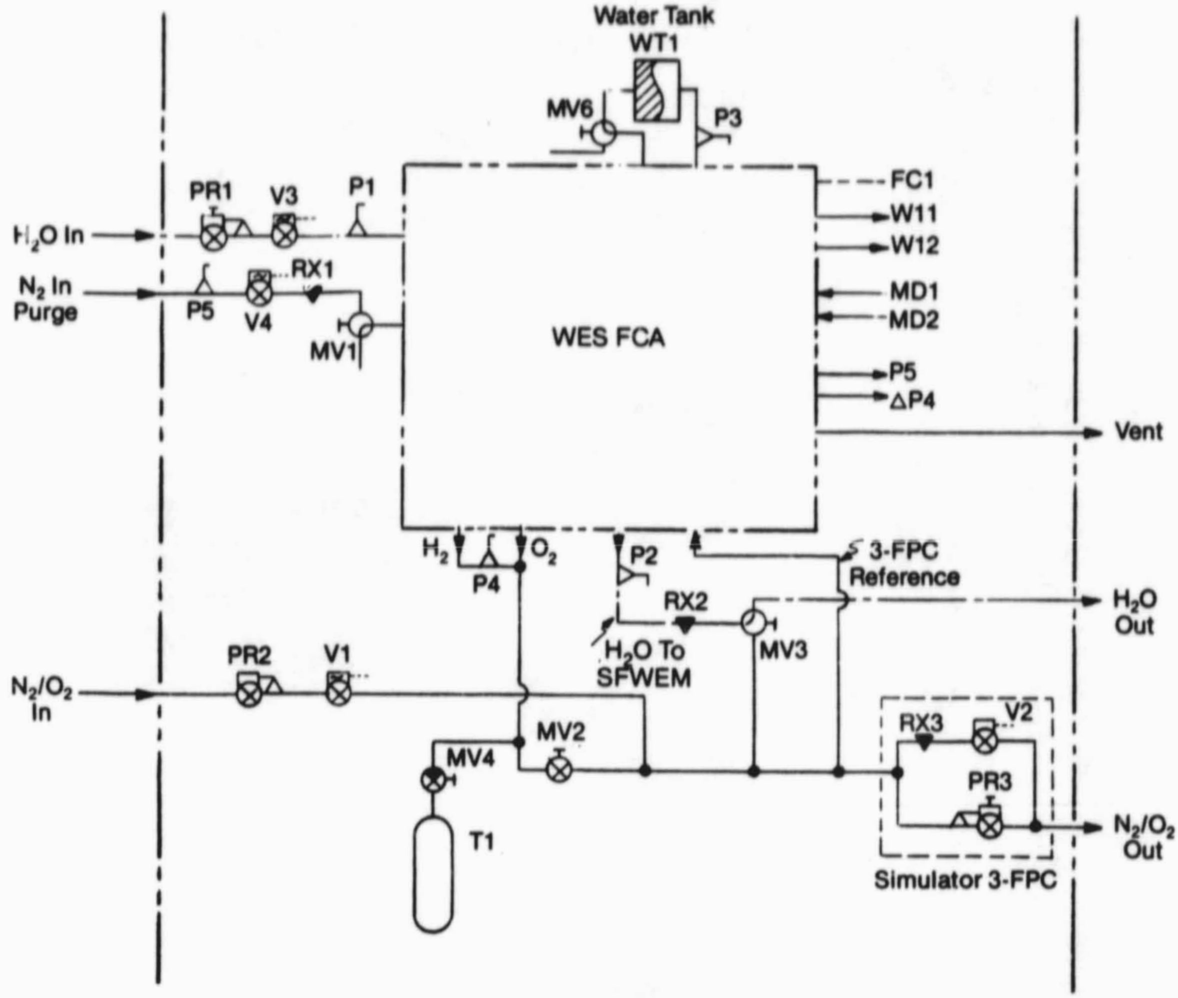

FIGURE 27 WES FCA TEST STAND MECHANICAL SCHEMATIC

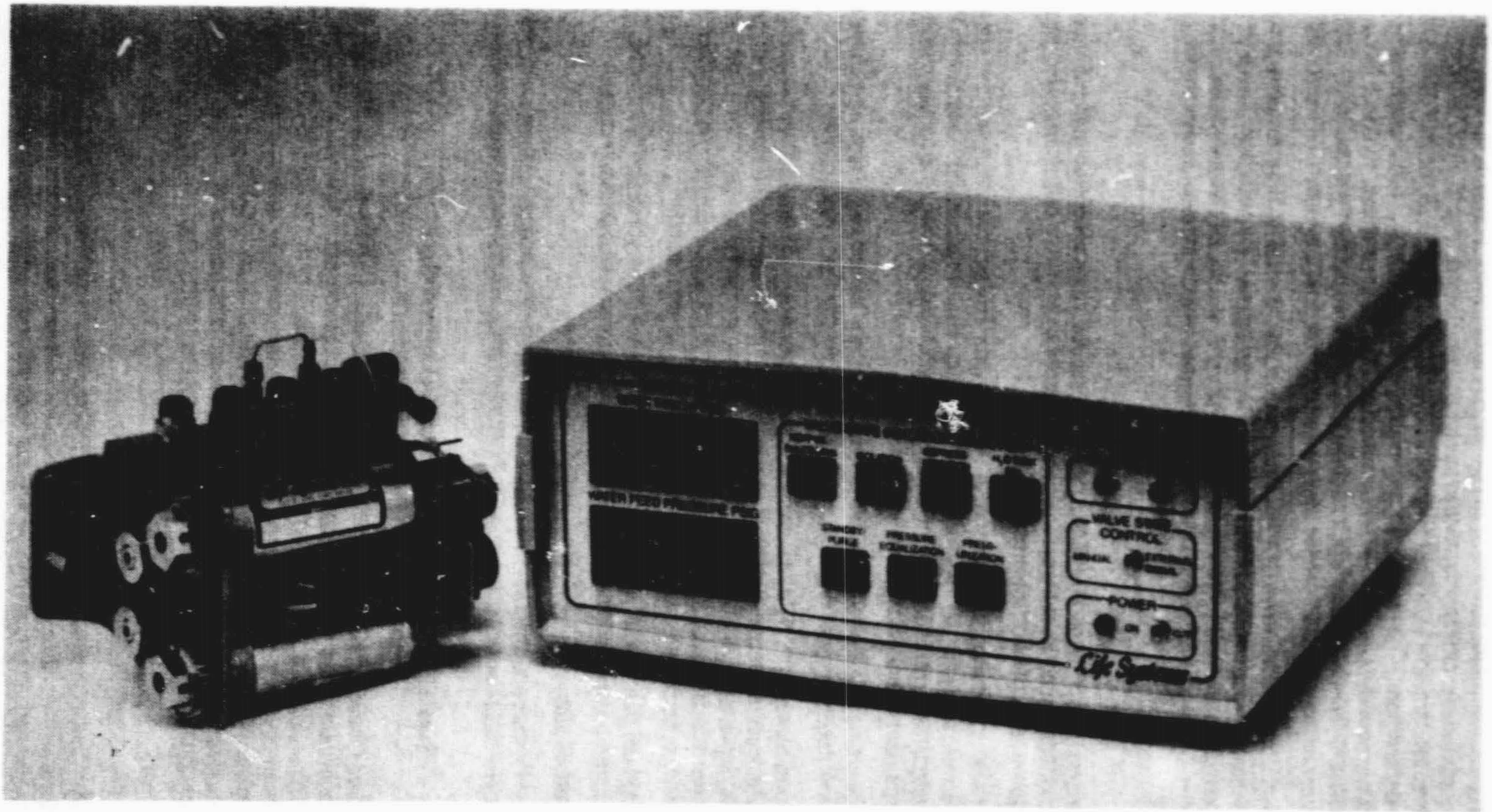

FIGURE 28 WATER ELECTROLYSIS SUBSYSTEM FLUID CONTROL ASSEMBLY AND ELECTRONIC CONTROLLER

The Controller accepts front panel commands to position the cam shafts to any of eight given states when in the manual mode, or accepts commands from the Actuator Exerciser to switch to one of the four operating modes: Shutdown, Purge, Normal or Standby. Automatic sequencing and feedback cam shaft position control for all of the allowed mode transitions are executed by the internal computer. Monitoring of the two cam shaft positions and the water tank differential pressure are utilized to properly execute these transitions. The power supply incorporates provisions to run the system in case of a power outage. Nickel/cadium batteries are trickle-charged under normal conditions and provide 24 VDC to the cam shaft motors and five VDC to the regulated DC/DC power supply which allows the Controller to position the WES FCA in the shutdown mode upon detection of an AC power loss. The Controller electrical block diagram is shown in Figure 29.

Actuator Exerciser. An Actuator Exerciser, shown in the upper-right hand corner of Figure 26 and in Figure 30, was fabricated to provide the supervisory timing functions for the WES FCA test stand. The Actuator Exerciser generates command signals to the WES FCA controller, directing it to the shutdown, purge, standby or normal states of operation. The sequences of these states are fixed by internal wiring, while the residence time in each state is adjustable from 10 minutes to 60 minutes by a front panel control.

WES FCA Evaluation

The WES FCA testing characterized the ability of the FCA to provide consistent operation through multiple cycles. Prior to beginning the testing, the FCA and test stand were integrated and functionally checked. All transducers, gauges and meters were calibrated to ensure the generation of accurate test data.

Checkout Testing. As part of checkout testing, all components were inspected as received. After the unit was assembled, static pressure tests were performed to verify the internal sealing capabilities of the valves. Leakage through two of the valves was noted during this phase of testing. The valve bores in the valve body were re-worked to improve the surface finish; this effectively eliminated leakage past the O-rings of the valves.

Shakedown Tests. The shakedown test was conducted to ensure integrated FCA/test stand operation. Valve positions were automatically switched every ten minutes for 24 hours. Air was used as the test gas at both inlets.

Cyclic Test. Cyclic testing was conducted with N_2 and water, to ensure simulation of actual operating conditions. The WES FCA was automatically cycled through each of its valve spool positions. A typical operating cycle is shown in Figure 31. Residence time in each operating state was varied periodically through the cyclic test to vary the occurrences of water fills as well as to vary the duration of the operating cycle. Each cycle simulates WES operation from shutdown, through purge to normal, then back to shutdown. This cycle was repeated over 200 times during testing.

Test Results. The results of 30 days of cyclic testing, which included 219 operating cycles and 432 water fill sequences, are summarized in Table 13. Overall, the unit performed its mechanical functions well over many cycles.

Conclusions and Recommendations

The WES FCA is a reliable vehicle for the reduction of water electrolysis subsystem weight, volume and power consumption. It demonstrated effective and successful control of fluid flows. Extended endurance testing is recommended as a follow-on effort.

Static Feed Water Electrolysis Unitized Core/ Composite Cell Development

The objectives of the unitized Core Development were to achieve reproducible and predictable SFWES performance over extended ranges of differential cell pressures and to reduce overall cell complexity and assembly time. As a goal, the unitized core was to exhibit pressure differential capabilities of up to 83 kPa (12 psid). The unitized core concept enables such improvements by providing permanently bonded, versus mechanically sealed, cell component construction. This technology prevents leakage across the edges of the cell matrix and, therefore, permits tolerance to higher H_2/System and O_2/System differential pressures. It also provides uniform matrix support and thickness, both up to and including the edges of the matrix. The following subsections describe the development and evaluation of the unitized core/composite cell technology at the single-cell and module levels.

Core Design

Major drivers for composite SFWE cell construction were enhanced pressure differential capabilities and simplification of final cell assembly. Primary emphasis was directed toward selection of compatible materials and the fabrication concept for the unitized core, the heart of the cell. The baseline SFWE composite cell—to be discussed in a later section of this report—does not include or require a unitized water feed compartment component. However, to fully evaluate the SFWE composite cell capabilities and concepts, materials selection, preliminary methodology and equipment were defined for fabricating both a unitized "Cell Core" and a unitized "Feed Core." The Cell Core consists of the anode electrode/cell matrix/cathode electrode composite; the "Feed Core" consists of a support screen/feed matrix/support screen composite.

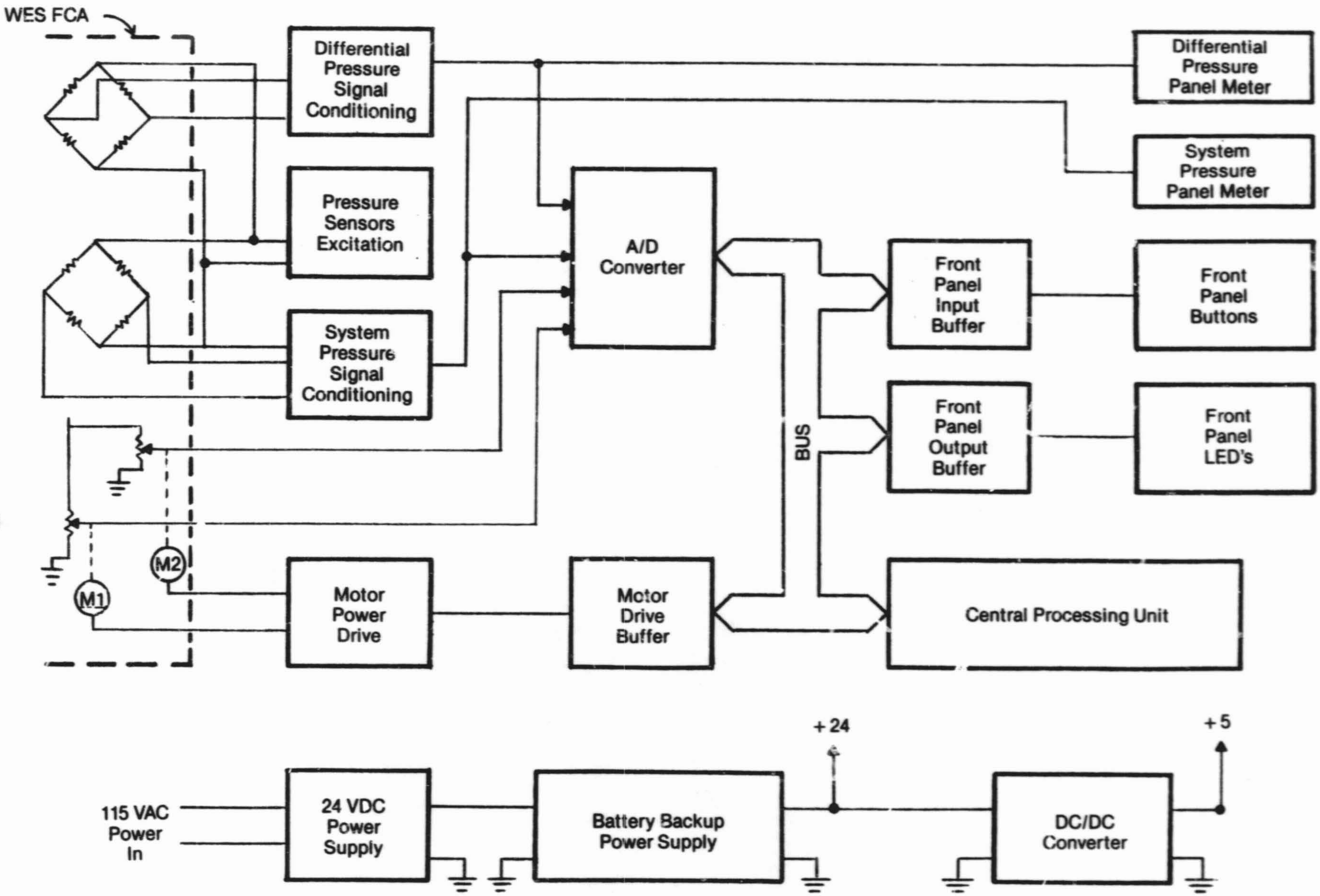

FIGURE 29 WES FCA CONTROLLER ELECTRICAL BLOCK DIAGRAM

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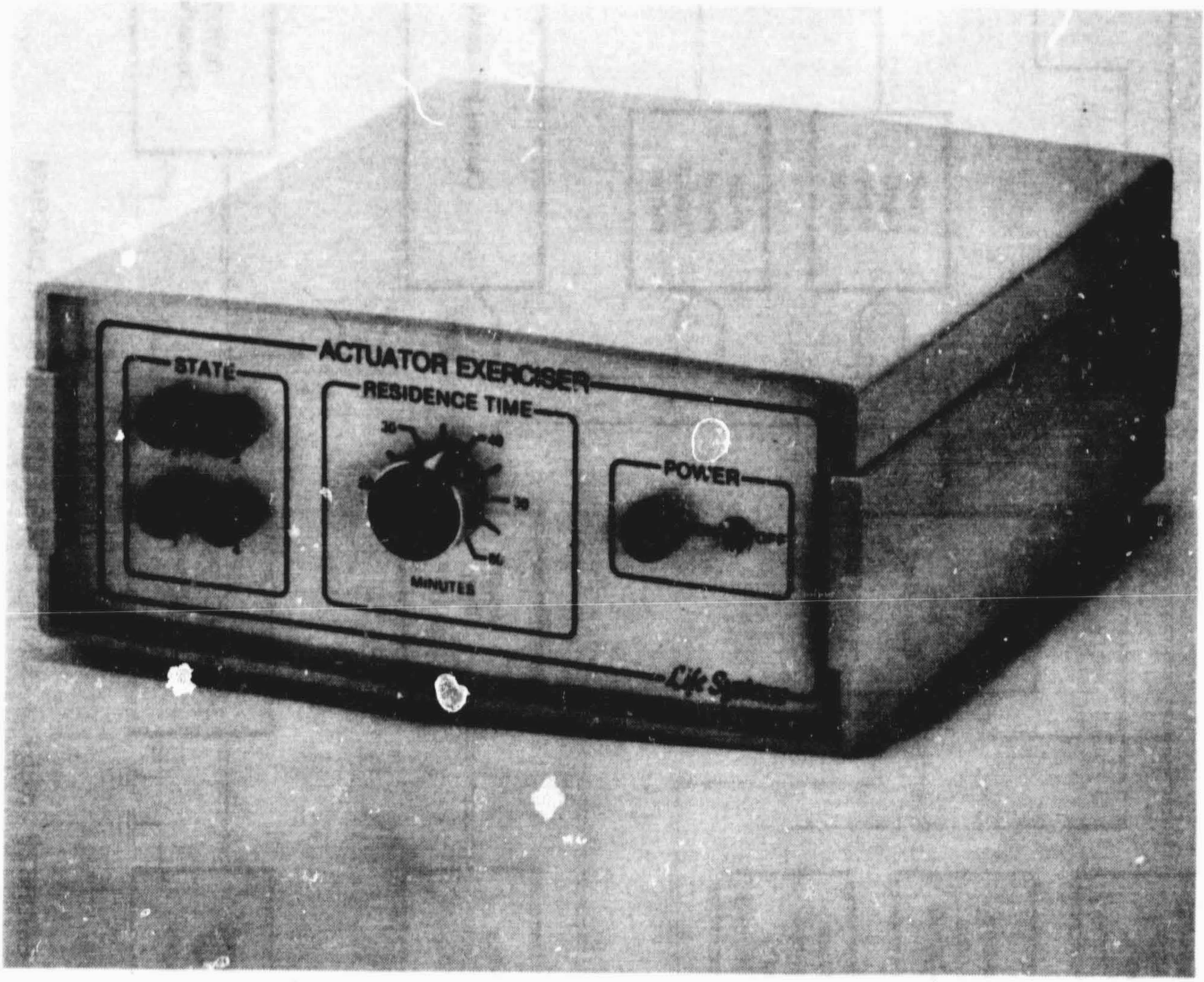

FIGURE 30 WATER ELECTROLYSIS SUBSYSTEM FLUID CONTROL ASSEMBLY ACTUATOR EXERCISER

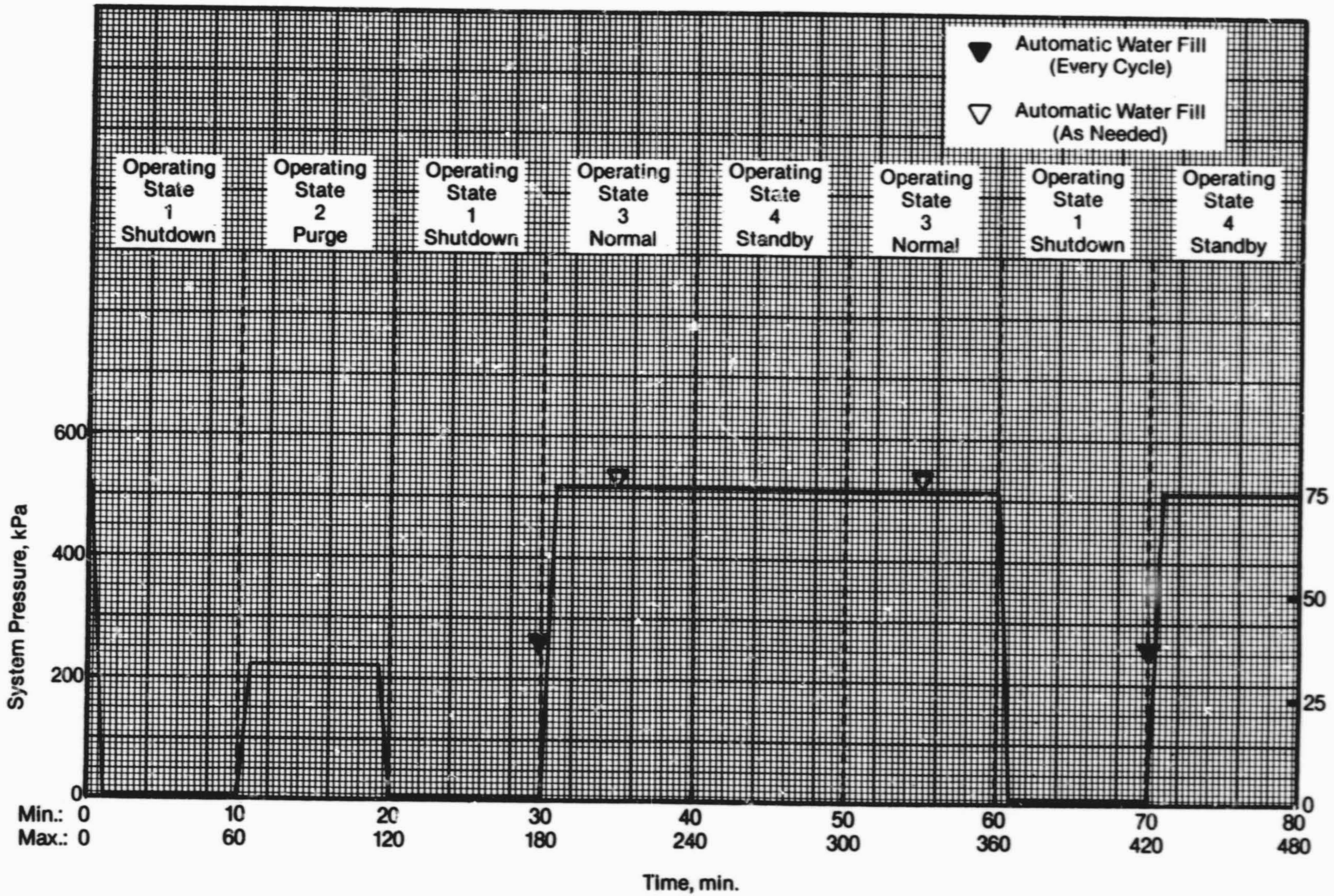

FIGURE 31 WES FLUID CONTROL ASSEMBLY OPERATING CYCLE

TABLE 13 WES FLUID CONTROL ASSEMBLY SEQUENCE OF TESTS AND TEST RESULTS SUMMARY

Sequence of Tests

Test No.	Description	Duration	Residence Time, min	Gas Selection: N_2 Purge	Gas Selection: N_2/O_2	Monitored Parameters
1	Checkout	4 hours	15	Air	Air	P1-5
2	Shakedown	24 hours	10	Air	Air	P1-5
3	Cyclic	30 days	Varied	N_2	N_2	P1-5

Test Results Summary

Parameter	Observations During Over 200 Complete Cycles
Valve Positioning	Consistent and accurate. Position indicators functioned satisfactorily.
Valve Spool Torque	Required torque less than motor clutch torque; therefore, somewhat higher valve spool sealing (increased O-ring compression) is permissible.
Valve Leakage	Satisfactory; no forward leakage noted at operating pressures.
Pressure Regulation	Consistent under flow conditions.
Flow and Pressure Measurement	All sensors functioned throughout testing.

The unitized Cell Core concept is illustrated in Figure 32 and the unitized Feed Core concept is illustrated in Figure 33. The overall concept for the composite single cell evaluation is illustrated in Figure 34.

Core Fabrication Technique

Initial fabrication trials were performed at the 7.6 cm x 7.6 cm (3 in x 3 in) core-size level. Following an iterative process of procedure and material evaluation and improvements, a unitized core/composite cell was successfully fabricated at the 93 cm^2 (0.1 ft^2) cell-size level.

Fabrication of the unitized cores involved the application of epoxy-impregnated fiberglas frames and rims around the perimeters of the cell electrodes, matrices and support screens, as shown in Figures 32 and 33. These subassemblies were then combined with more epoxy and polysulfone to form two, separate unitized cores: a Cell Core and a Feed Core. This approach provided uniform support of the cell matrix over its entire area, thereby providing maximum gas pressure sealing characteristics of the electrochemical cell.

The key structural material selected for the unitized cores was the epoxy-impregnated fiberglas. Of the many fabrication materials studied, the epoxy-impregnated fiberglas was the most compatible with the operating environment of the SFWE cell and exhibited the strength and rigidity needed. The epoxy/fiberglas did exhibit some porosity, however, so a compression seal between the various components of the composite cell was selected over a chemical bonding type of seal. Critical points in the fabrication processes included maintaining proper widths, thicknesses and uniformities of individual components and the subsequent unitized core. The parameters were controlled using varied, combined applications of heat and pressure. Care was taken to ensure that all components of each core were properly aligned, that cell matrix and electrode active areas were free from epoxy and polysulfone, and that effective seals were achieved around the edges of each unitized core.

Full size (93 cm^2 (0.1 ft^2)) cell and feed cores fabricated using these materials and procedures demonstrated differential pressure capabilities in excess of 210 kPa (30 psid), well above the design goal of 83 kPa (12 psid). Sealing limitations of the test fixture used for the differential pressure evaluations limited the determination of a finite breakthrough pressure for each of the unitized cores. However, results of the differential pressure testing were a direct indication of the uniform support provided to the matrices in each of the unitized cores.

Concept Evaluation Tests

A single SFWE composite cell was fabricated as previously discussed using LSI Advanced electrodes. The components of this single cell are shown in Figure 35. The single cell test program was carried out primarily to verify concept and hardware performance and included calibration and checkout testing, shakedown tests, design verification testing, parametric testing and endurance testing. A discussion of the results of these tests follows.

Calibration/Checkout Tests. This phase of the testing program included calibrations and mechanical and electrical checks of the single cell-test TSA.

Shakedown Testing. This phase of testing included setting and maintenance of stable interface conditions and 24-hour uninterrupted cell operation at the nominal design point. No major problems were encountered.

Design Verification Testing. Design verification testing of the unitized core/composite single cell included a cell voltage versus current density span. This data is shown in Figure 36 in comparison to typical advanced electrode performance. At equal product gas pressures, the performance of the cell falls within the expected operating level for advanced electrodes. At a PO_2—PH_2 of 10 psid, the performance of the cell falls just outside the advanced electrode performance band. This is as expected, however, since cell voltage increases as the O_2-H_2 pressure differential increases.

Parametric Testing. Parametric Testing included characterization of cell performance as a function of O_2/H_2 differential pressure at different current densities. This data is shown in Figure 37. During the design verification and parametric tests, the unitized core/composite single cell demonstrated the ability to operate at the design goal differential pressure of 83 kPa (12 psid).

Endurance Testing. A 750-hour endurance test of the unitized core/composite single cell was performed. The cell was operated at O_2/H_2 differential pressures up to 83 kPa (12 psid). Nominally, the O_2/H_2 differential pressure was maintained at 69 kPa (10 psid). The test data is shown in Figure 38. Notes called out on Figure 38 are discussed in Table 14. The single cell endurance testing demonstrated the ability of the SFWE unitized core/composite cell to operate for extended periods of time at O_2/H_2 differential pressure up to 83 kPa (12 psid). As anticipated, increased cell voltage was experienced due to the increased O_2/H_2 Δ P. The increasing cell voltages experienced during the latter portions of the endurance test were attributable to increased internal resistances and leakage caused by failure to maintain a tight seal between the unitized Feed Core and the cell frame.

Conclusions. The pressure and performance testing of the unitized core confirmed the basic material selection and overall concept of the SFWE composite cell.

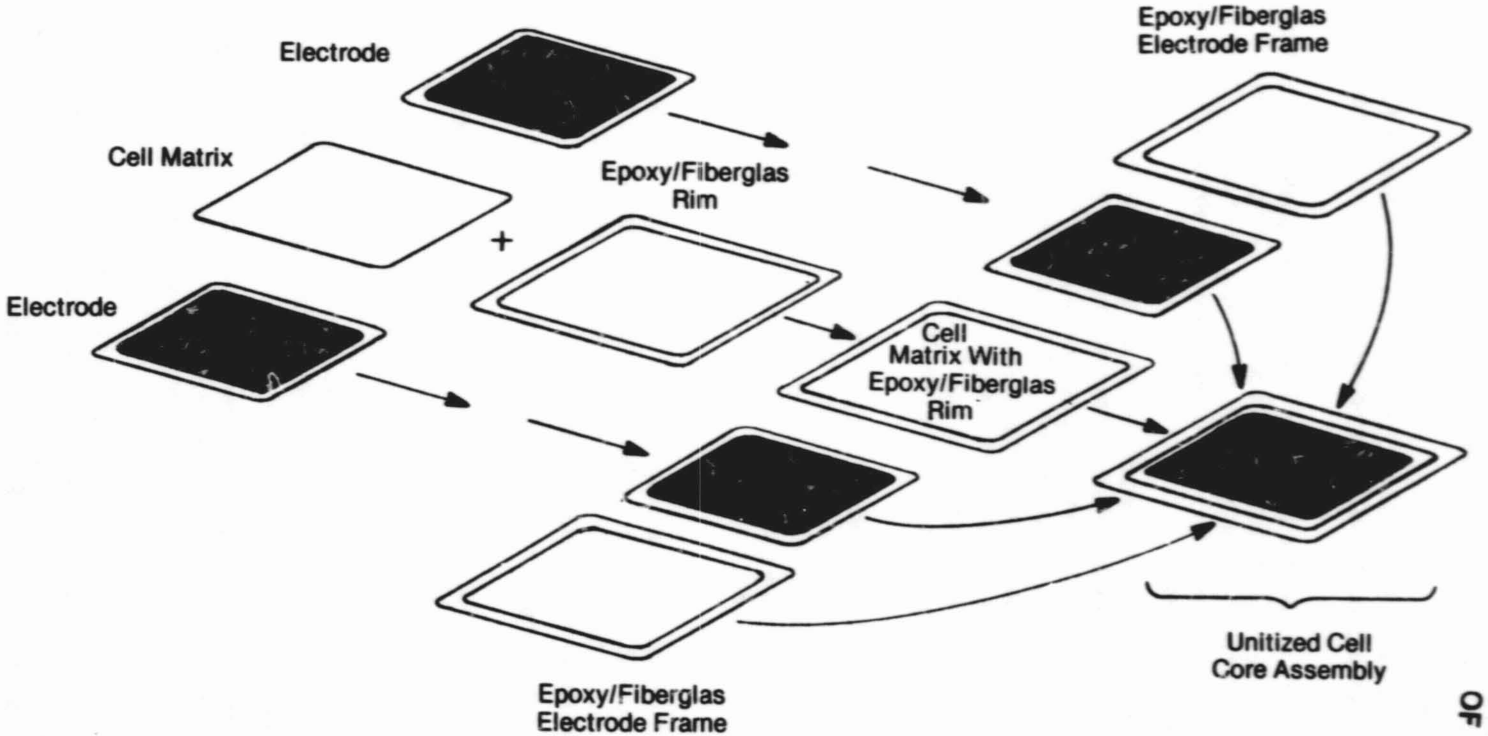

FIGURE 32 UNITIZED CELL CORE CONCEPT

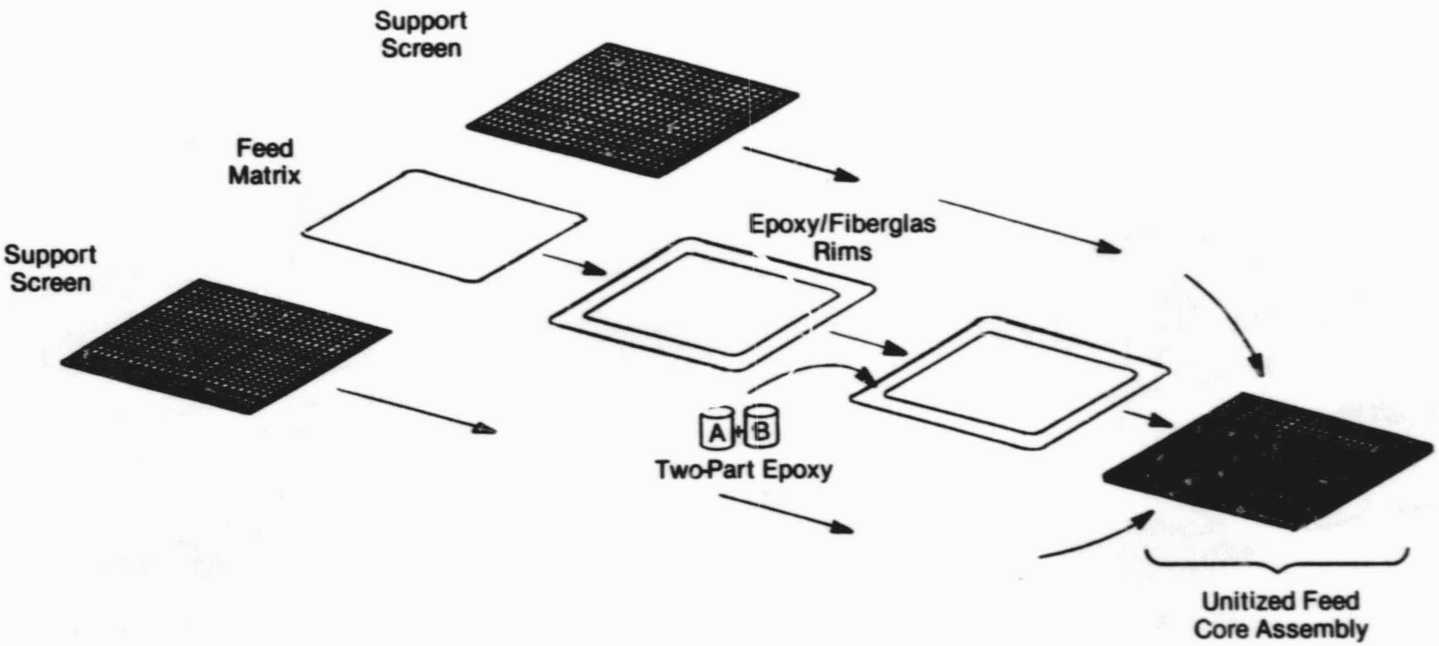

FIGURE 33 UNITIZED FEED CORE CONCEPT

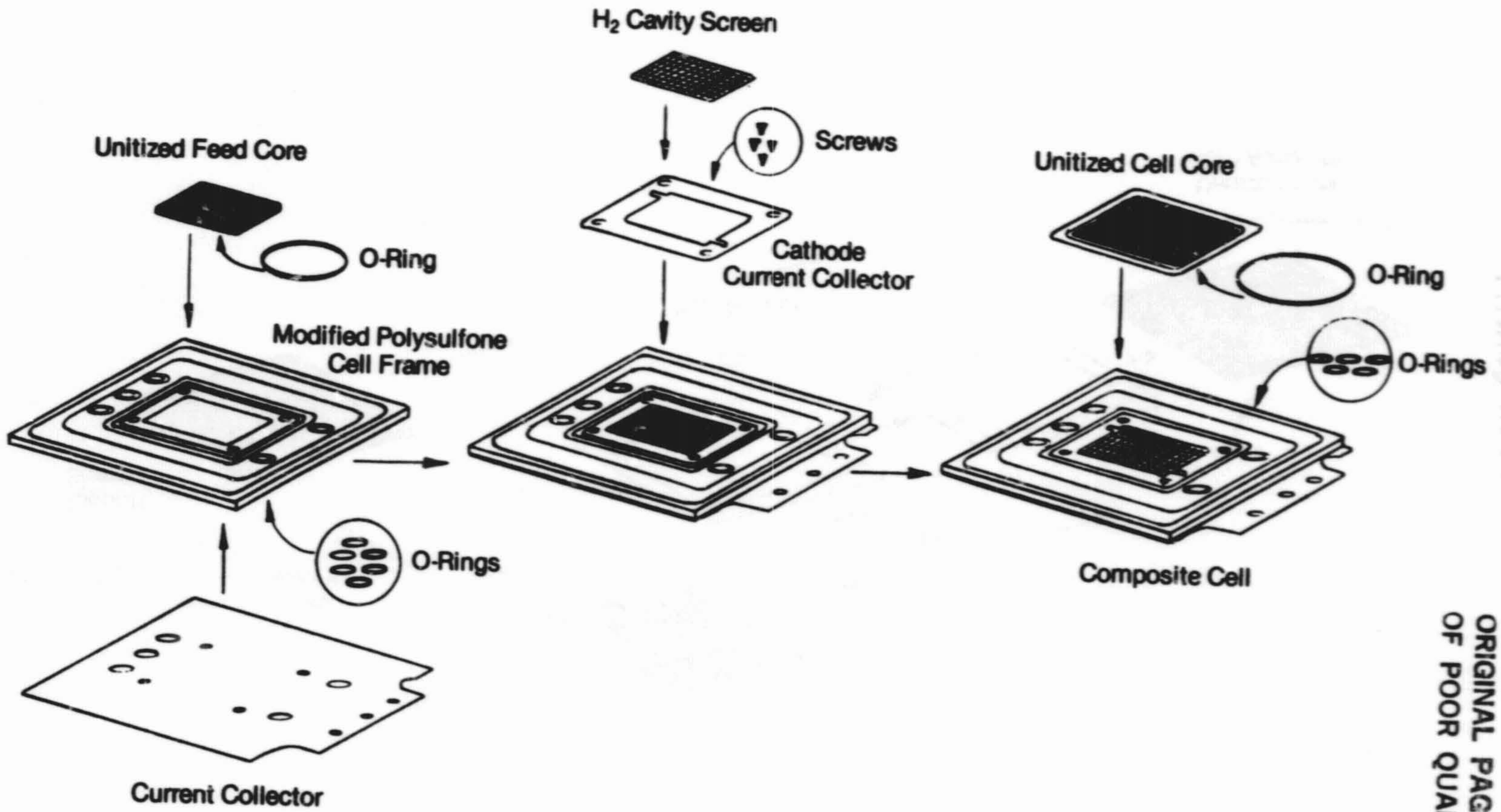

FIGURE 34 SFWE UNITIZED CORE/COMPOSITE CELL EVALUATION CONCEPT

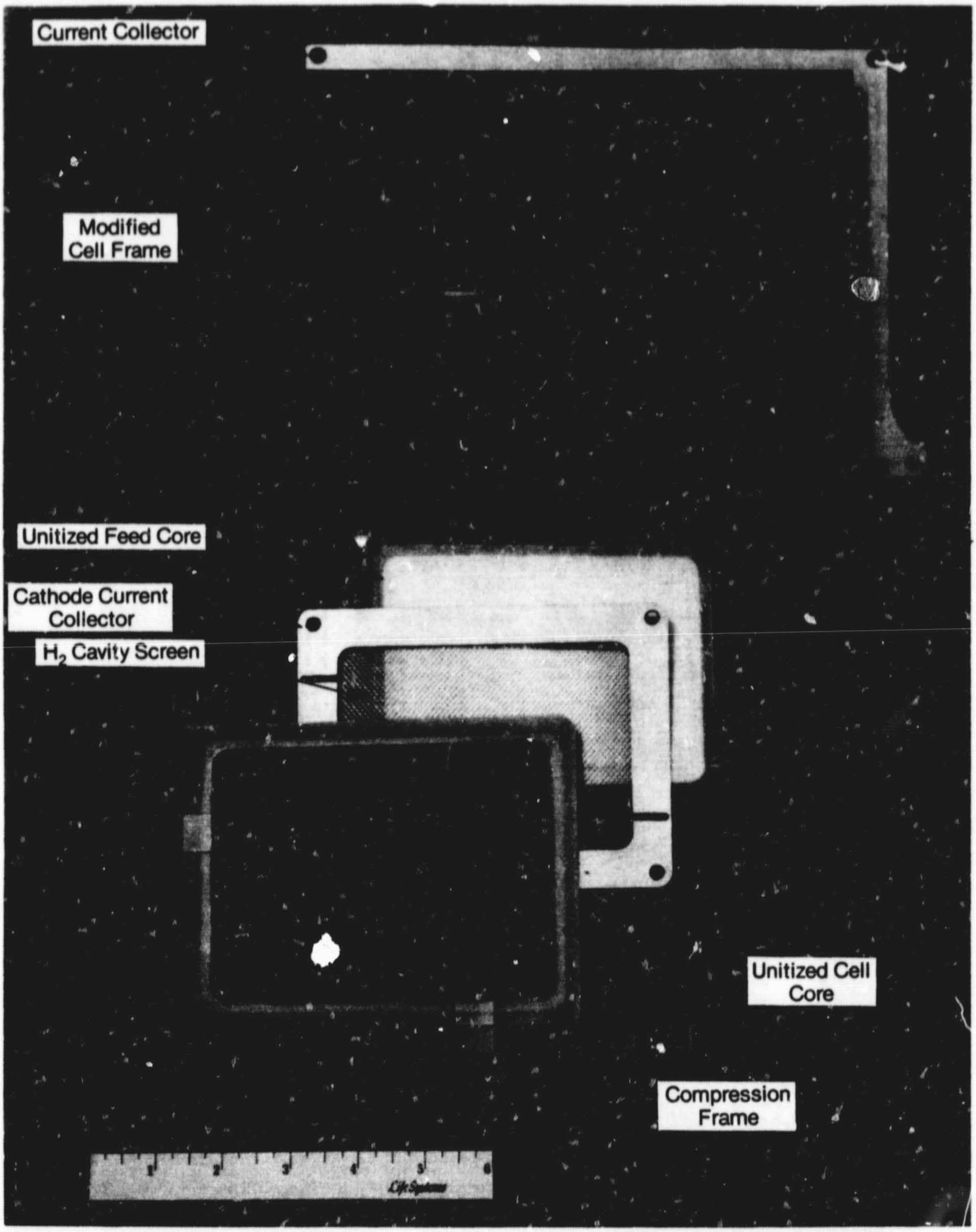

FIGURE 35 SFWE UNITIZED CORE EVALUATION CELL

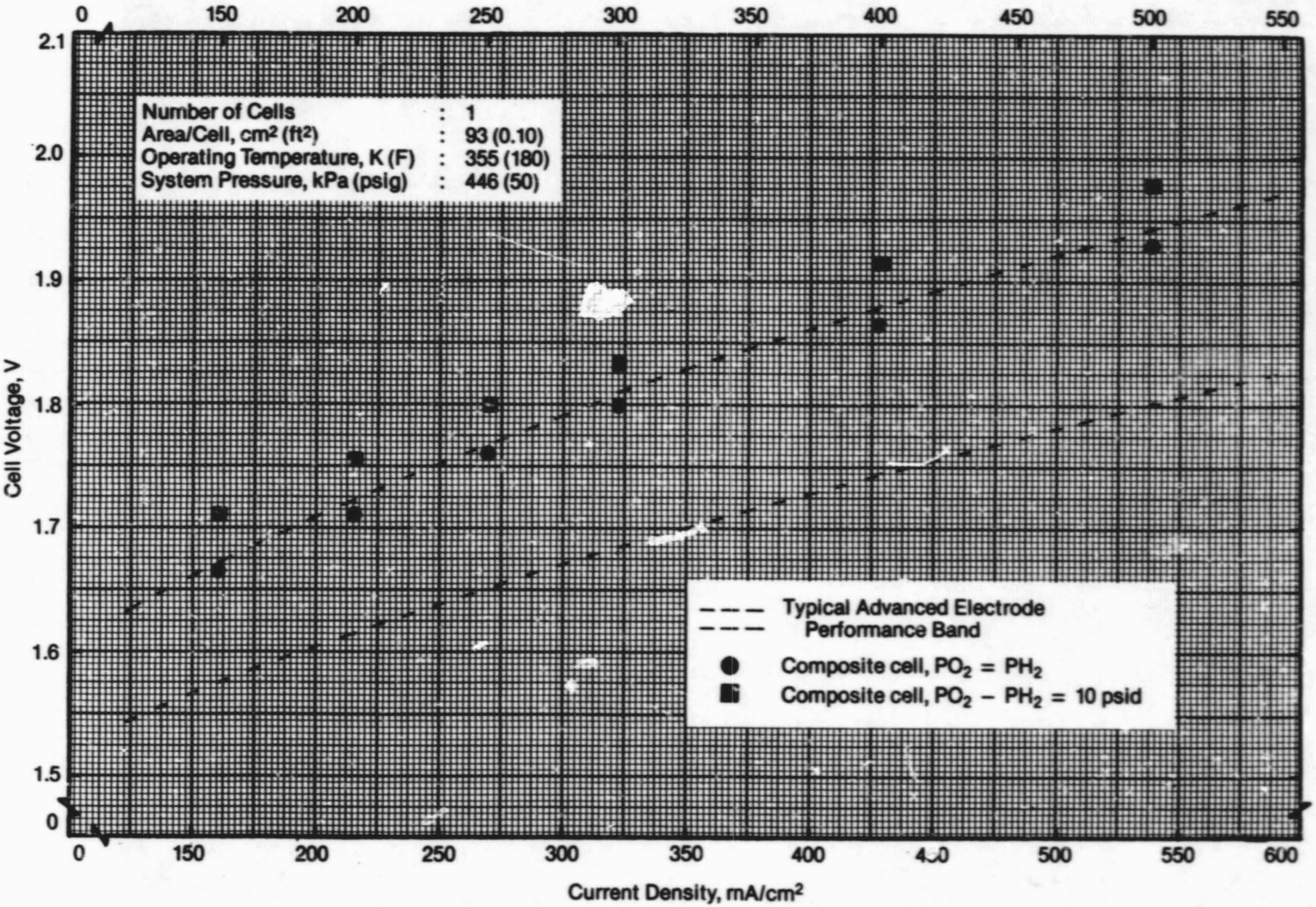

FIGURE 36 UNITIZED CORE/COMPOSITE SINGLE CELL PERFORMANCE

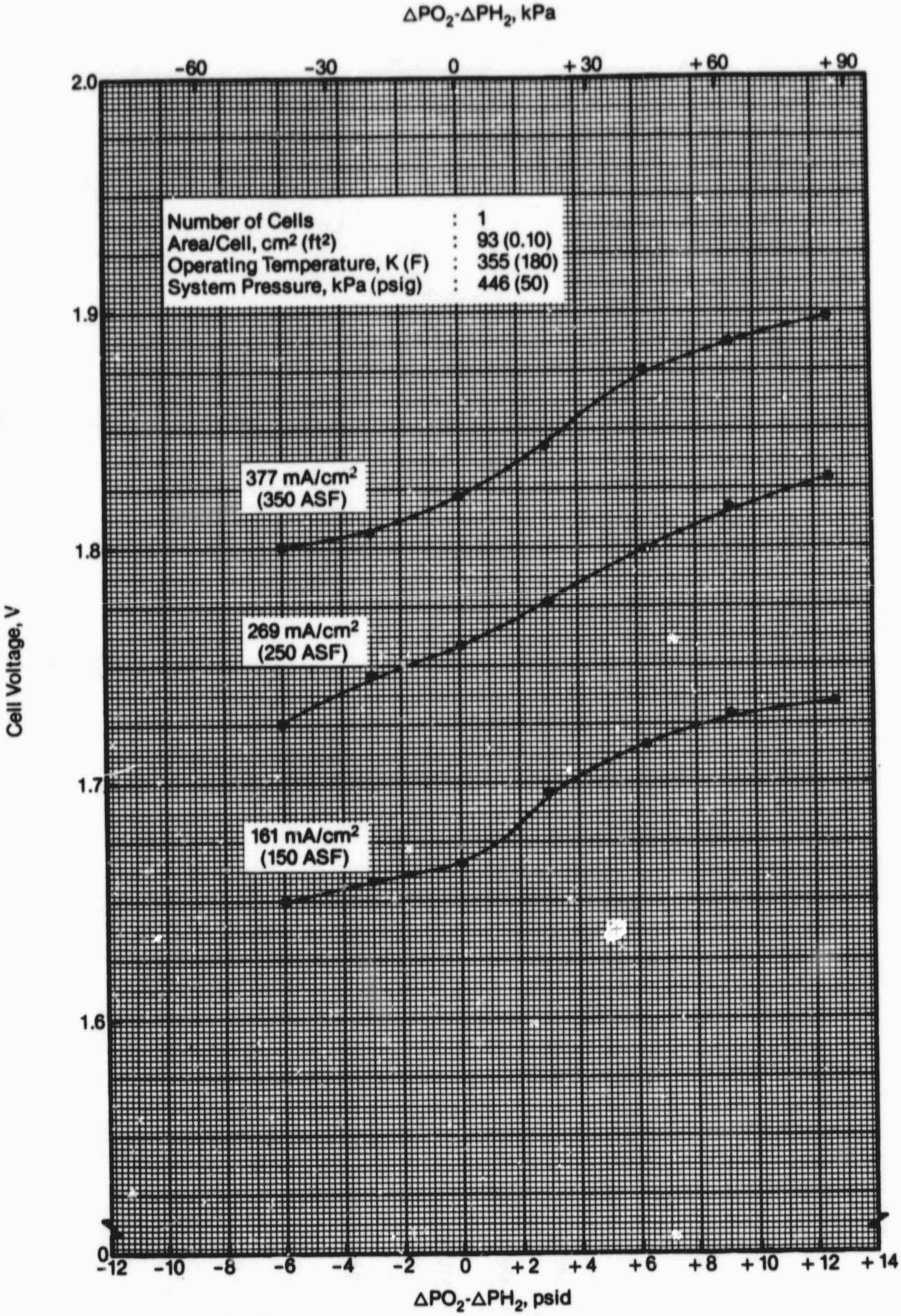

FIGURE 37 UNITIZED CORE/COMPOSITE SINGLE CELL: CELL VOLTAGE VERSUS O_2/H_2 DIFFERENTIAL PRESSURES

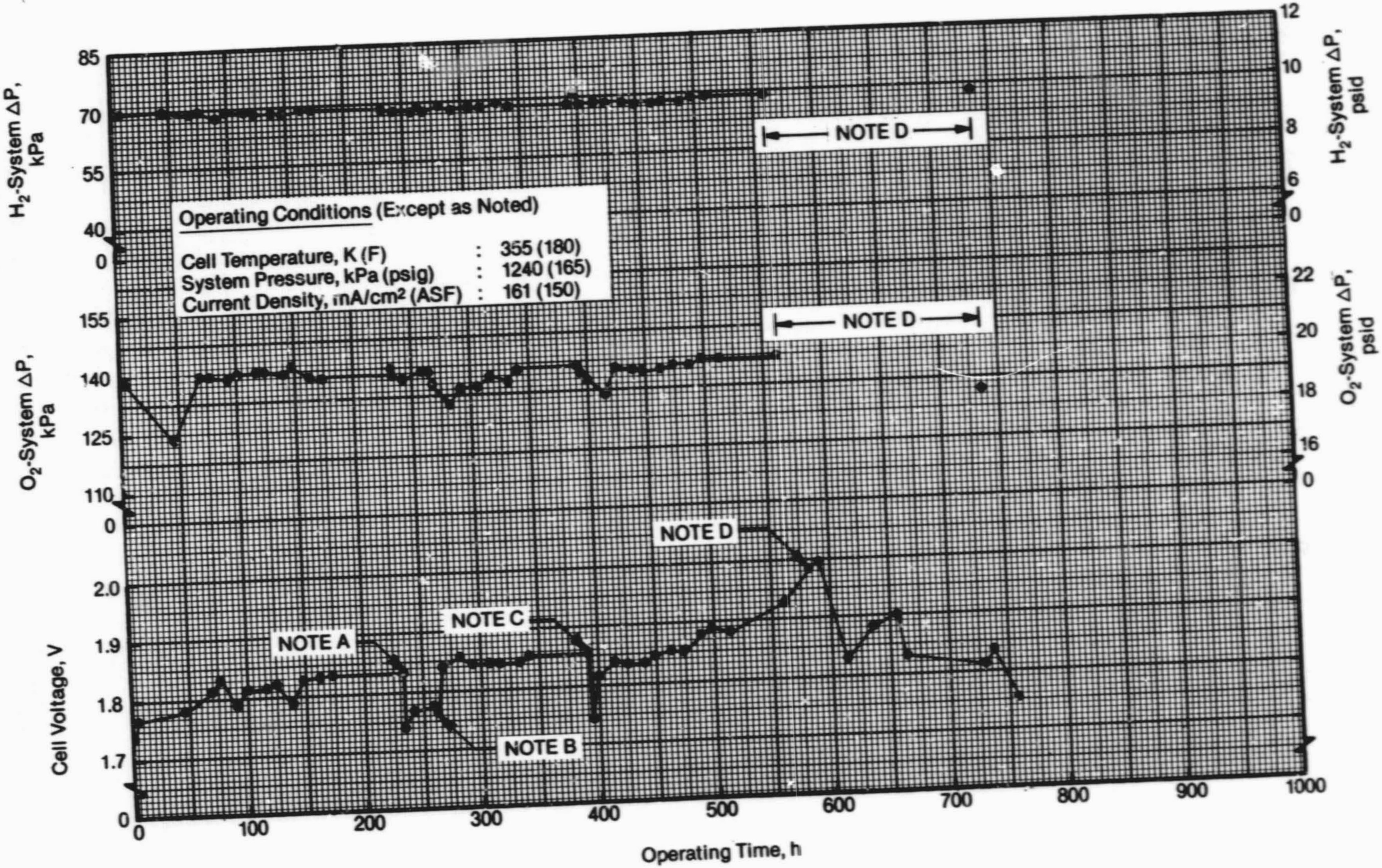

FIGURE 38 WATER ELECTROLYSIS UNITIZED CORE/COMPOSITE SINGLE CELL ENDURANCE TESTING

TABLE 14 COMPOSITE SINGLE CELL ENDURANCE TEST DATA NOTES
(Figure 38)

Note	Explanation
A	Test stand shutdown due to coolant recirculating pump failure. Coolant pump was m[illegible] restarted and testing was continued.
B	System pressure increased, as scheduled, to nominal static feed operating conditions of 1,240 kPa (165 psig). Prior to this point, the system pressure had been maintained at 446 kPa (50 psig) to evaluate effects of pressure on performance.
C	Test stand shutdown due to decoupling of the coolant recirculating pump. The pump was repaired and testing was continued.
D	Increasing cell voltage was noted. To investigate the trend, the cell ΔPs were returned to baseline conditions (O_2-System ΔP from 20 to 4 psid; H_2-System ΔP from 10 to 2 psid). No improvement in cell voltage was noted. Further activities designed to recover cell performance included reduction of cell current and feed water compartment recirculation. Cell voltage decreased initially followed by steady increase. At the conclusion of testing, the cell was disassembled and it was noted that the seal between the unitized feed core and the cell frame had deteriorated. This weakness was resolved as part of the program activities.

Composite Cell Baseline Design

The long-term goal for SFWE has been the feed water electrolyte (KOH) elimination technique. Since this technique does not require a feed matrix/unitized Feed Core component in the static feed cell, a solution for a sealing technique for unitized Feed Cores which, ultimately, would not be required in SFWE cells, was not a necessary step in SFWE cell development.

Accordingly, the baseline SFWE composite cell consists of a baseline SFWE cell feed matrix and feed matrix support screens and the unitized Cell Core previously developed. The composite cell baseline design assembly concept is illustrated in Figure 39. It can be seen that the cell illustrated in Figure 39 is similar to that illustrated in Figures 34 and 35 previously presented, with the exception that the unitized Feed Core and O-ring illustrated in Figures 34 and 35 have been replaced by an individually-installed support screen/feed matrix/support screen combination.

The composite cell includes an injection-molded polysulfone plastic frame for manifolding and distributing process gases and internal liquid coolant, current collectors for delivering current to the cell and assorted O-rings and support screen. The polysulfone cell frame provides an isolated internal liquid coolant cavity for the SFWE cell. Both anode and cathode current collectors are gold-plated nickel and are included as part of the final composite cell assembly. Process fluid isolation is accomplished by an arrangement of O-rings that provide seals between the H_2 cavities and feed cavities of each individual cell as well as between each composite cell in a module stack.

Baseline Six-Cell Composite Cell Module Testing

A six-cell, composite cell module was assembled using modified cell frames, Life Systems' baseline feed matrices and support screens in the cell feed compartment and unitized Cell Cores. This baseline module was then placed under test.

The objective of the test program was to evaluate the performance of the baseline SFWE composite cell module at nominal operating conditions for 30 days, as a goal. Endurance test data for the baseline composite cell module is shown in Figure 40. After 720 hours at nominal operating conditions, the module average cell voltage was consistently within the advanced electrode performance band. The baseline operating conditions for Life Systems' SFWE modules are shown in Table 15. Two shutdowns occurred during the limited endurance test; these are summarized in Table 16. Were it not for an uncontrollable building power failure and subsequent operator "handling" errors, it is projected that the baseline composite cell module would have operated for the full 30 days without a shutdown. At the conclusion of the endurance test, a current density span was performed. This data is shown in Figure 41. Operation at elevated O_2/H_2 differential pressures was not performed since it was neither consistent with SFWEM baseline operating conditions nor compatible with the baseline composite cell design.

Conclusions and Recommendations

Based upon the endurance test data, the static feed water electrolysis baseline composite cell design demonstrated effective performance characteristics. It successfully demonstrated the next step in the progression toward more reliable and less complex SFWE cells. Further endurance and characterization testing at the module level is recommended as a follow-on effort.

Feed Water Electrolyte Elimination Demonstration

A technique for eliminating KOH from the water feed compartment of a SFWE cell was previously evaluated.(7) The concept of elimination of KOH electrolyte from the water feed compartment permits elimination of the separate coolant compartment by using the feed water, itself, to provide for temperature control, thus greatly simplifying the SFWES design.

The KOH Elimination Cell design and operation are similar to the SFWE baseline cell design (previously shown in Figure 1) and operation, with the exception that a porous membrane replaces the water feed matrix between the H_2 compartment and the water feed compartment. This membrane, which is highly resistant to bulk liquid flow, ensures isolation of the water feed cavity from the electrochemical cell while allowing water vapor transport, thus preventing cell electrolyte from mixing with the feed water. To maintain the liquid/gas separation between H_2 gas and feed water, the feed water compartment is typically maintained at 6.9 to 27.6 kPa (1.0 to 4.0 psi) above the H_2 gas pressure. In the baseline electrochemical cell, the feed water compartment is typically 14 kPa (2 psi) below the H_2 gas pressure.

Since the KOH elimination cell operates without the electrolyte concentration stabilizing effect of KOH self-regulation of water transport in the water feed compartment, adjustments in cell operation are required to maintain the cell electrolyte at optimum or near-optimum concentration. Temperature, current density and pressure influence the electrolyte concentration and influence the way the cell handles the water. Increasing the temperature of the feed water tends to both increase the amounts of water transferred from the feed water compartment and the amount of water transferred to the product gases for humidification. Increasing the current density increases the water produced at the anode which must be transferred either to the cathode or to the O_2 gas leaving the cell. Increasing the pressure decreases the amount of water removed through humidification. Thus, controlling the electrolyte concentration at the KOH elimination cell anode and cathode during electrolysis requires control over these parameters.

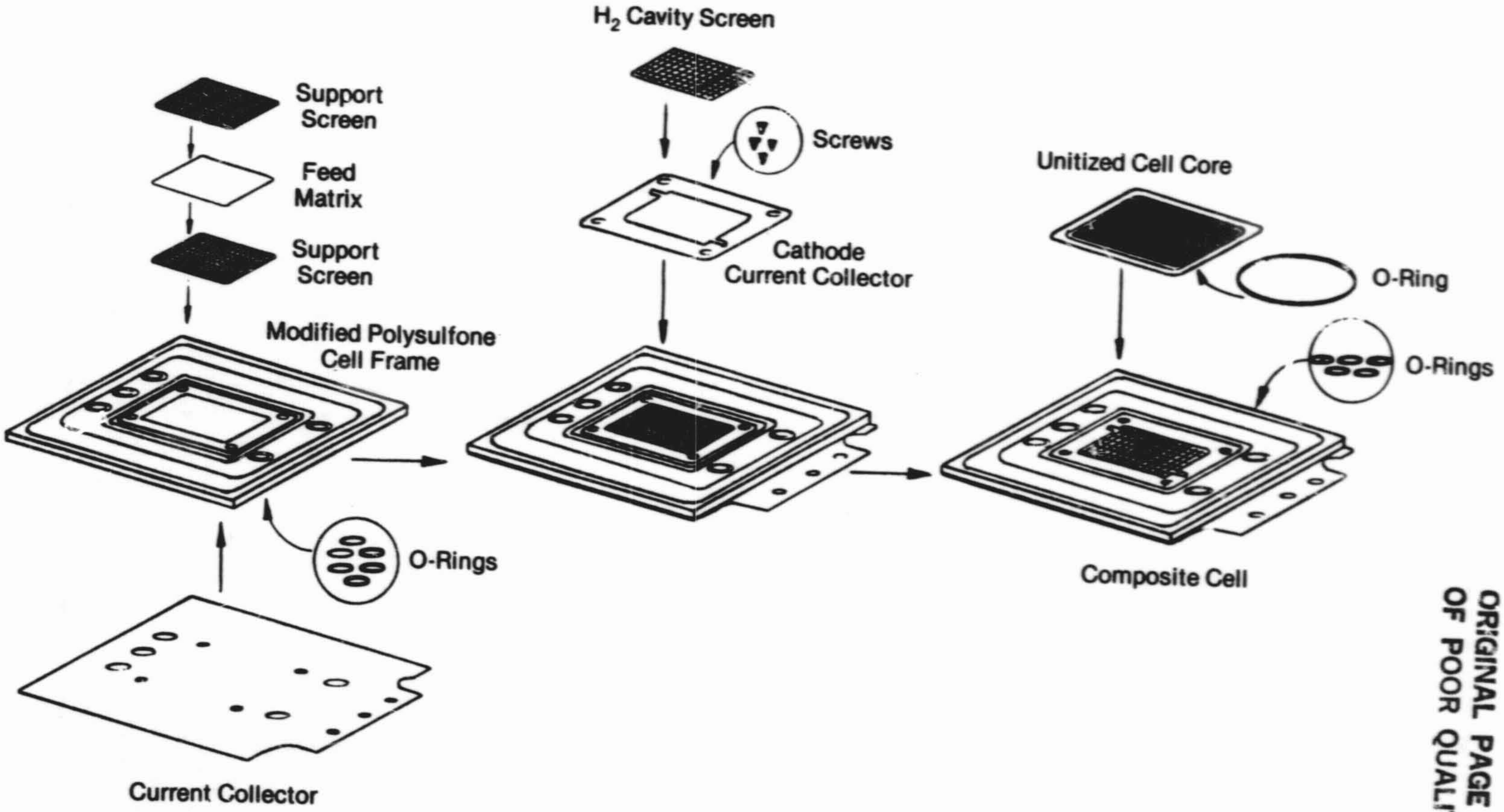

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FIGURE 39 SFWE UNITIZED CORE/COMPOSITE CELL BASELINE DESIGN CONCEPT

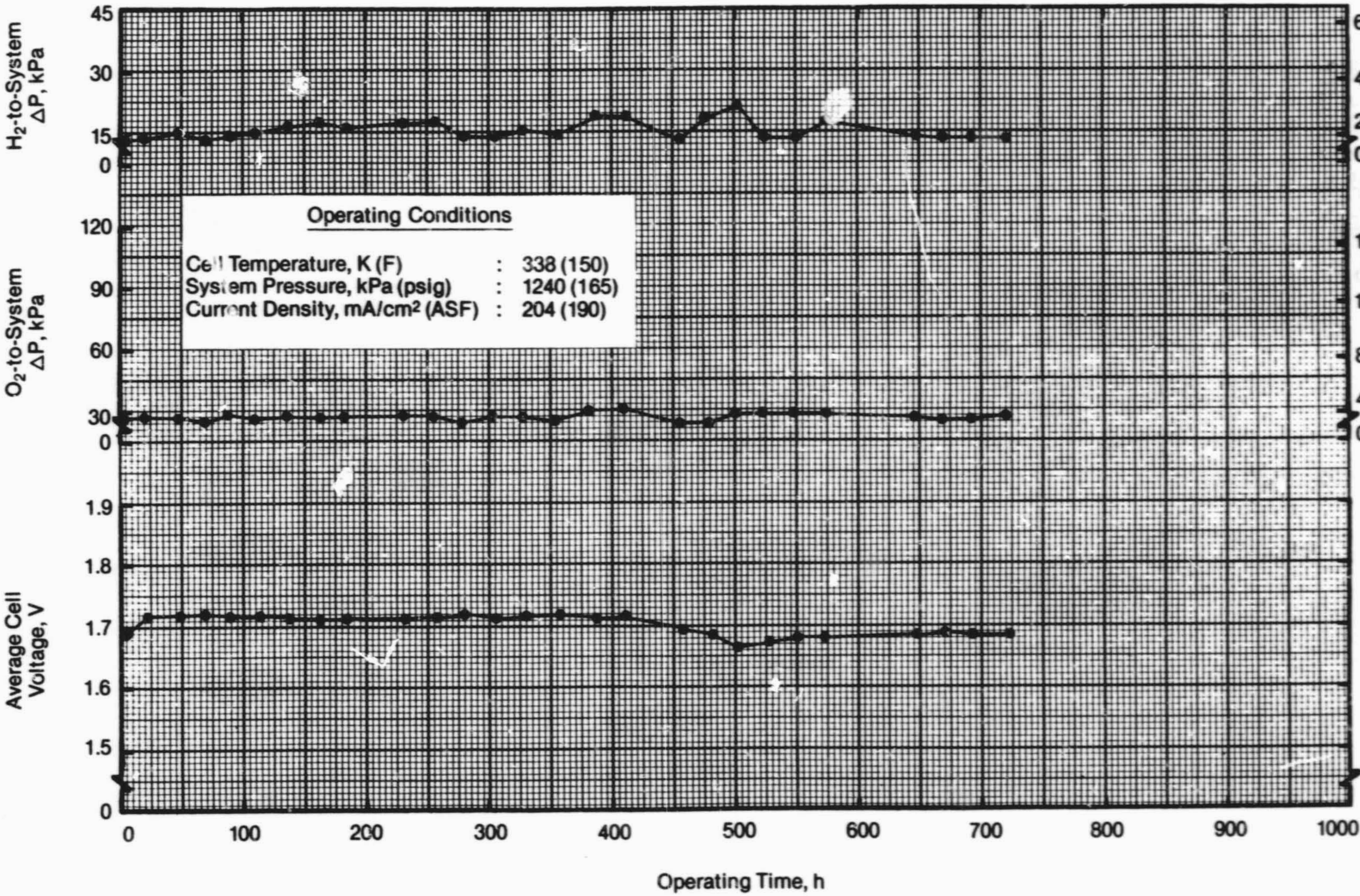

FIGURE 40 SFWE UNITIZED CORE/COMPOSITE SIX-CELL MODULE (BASELINE DESIGN) ENDURANCE TESTING

TABLE 15 BASELINE OPERATING CONDITIONS FOR LIFE SUPPORT STATIC FEED WATER ELECTROLYSIS MODULES

Parameter	Nominal Value
Temperature, K (F)	339 (150)
System Pressure, kPa (psia)	1,240 (180)
Current Density, mA/cm^2 (ASF)	205 (190)

TABLE 16 SFWE BASELINE COMPOSITE SIX-CELL MODULE ENDURANCE TEST SHUTDOWN LIST

Shutdown No.	Total Operating time, h	Continuous Operating time, h	Shutdown Symptom	Shutdown Cause/Action Taken	Down Time, d
1	412	412	Power interruption	Building power failure; module restarted	0.5
2	468	56	Low cell voltage	Test stand malfunction followed by operator oversight.	7.0
			High cell voltage	Technician error during module installation.	5.0
3	720	252		Completion of test.	

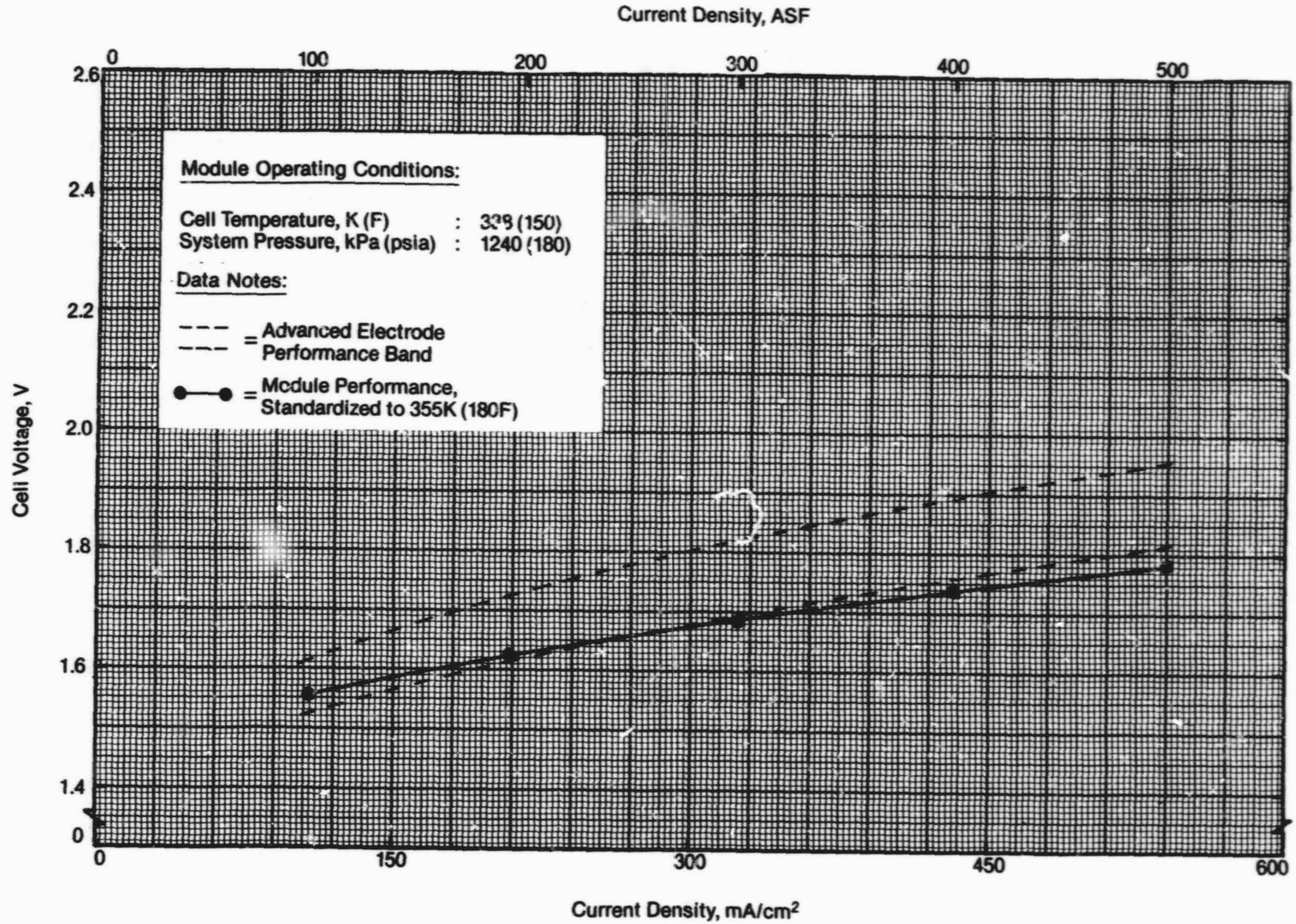

FIGURE 41 SFWE COMPOSITE SIX-CELL MODULE CURRENT DENSITY SPAN

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Baseline KOH Elimination Cell Design

The baseline design for the KOH elimination cell is shown in Figure 42. The baseline KOH elimination cell is quite similar to the baseline unitized core/composite cell design previously illustrated in Figure 39, with the exception that the feed matrix and support screens from the unitized core/composite cell design are replaced in the KOH elimination cell by the feed cavity porous membrane, the support screens and compression frame. The unitized Cell Core (electrode composite) concept is retained in the KOH elimination cell. The polysulfone cell frames are modified to permit installation of the porous membrane and its supporting hardware, rather than the feed matrix and support screens.

The design of the feed cavity porous membrane was improved over that used in the single cell tests conducted during the previous contractual effort. Tests of the earlier installation technique, while acceptable for ambient pressure single cells, showed unreliable sealing at a differential pressure of 35 kPa (5 psid) in high-pressure, multicell modules. Membrane sealing problems were resolved by incorporating the following modifications into the baseline cell design.

- Each porous membrane was chemically etched around its perimeter prior to bonding into the polysulfone cell frame. This provided superior adhesion over non-etched membranes.
- The membrane material was purchased with a non-woven polypropylene backing laminated to it. This backing minimized membrane shrinkage during the etching process and also minimized destructive shearing forces which occurred when the membrane was compressed between the upper and lower support screens.
- The mesh size of the upper and lower support screen material was changed from 70 x 70 mesh (previous baseline) to 159 x 159 mesh. The finer mesh size eliminated the tendency of the support screen to score and puncture the membrane film.

KOH Elimination Module Fabrication

A five-cell KOH elimination module was fabricated and assembled using the spare WEM fabricated under contract NAS2-10306. The cell frames were modified to use the porous membrane/feed compartment components and a unitized Cell Core assembly, as previously shown in Figure 42. The unitized Cell Cores were fabricated as previously discussed and shown in Figure 32, and incorporated Life Systems' Advanced Electrode as the cathode and a Super Electrode as the anode.

Test Support Accessories

A high pressure/high temperature test stand was designed and fabricated as part of the KOH elimination activities. This test stand is shown pictorially in Figure 43 and schematically in Figure 44. The test stand is multi-functional, providing the capability of testing feed water electrolyte elimination modules as well as baseline SFWEMs up to the six-cell level. The test stand has the capability of operation to 2,170 kPa (300 psig) and 422 K (300 F) and also has the capability to accommodate a high pressure/high temperature dew point sensor for monitoring the moisture conditions of the module via product gas dew point measurements.

The test stand has two liquid circulation loops: One loop supplies liquid coolant for maintaining module operating temperature and a second loop is used for delivering feed water to the cell. The cell coolant (water) is circulated by a pump (M2) through the module, and a water tank (WT-1) allows for coolant expansion and temperature control. Feed water is also circulated through the module by a second pump (M1), and a second water tank (WT-2) allows for feed water expansion and temperature control. Water is fed statically to the module from a storage tank (WT-3) to compensate for water consumed during the electrolysis process. For KOH elimination testing, a pressure greater than the H_2 pressure is maintained on the water feed cavity by maintaining a positive, above-H_2 pressure on the water storage tank.

KOH Elimination Module Testing

The objective of the test program was to demonstrate at the module level the concept of electrolyte elimination from the electrolysis cell water feed compartment. To demonstrate the KOH elimination concept, a five-cell module was assembled and tested. Characterization and endurance tests were conducted for 675 hrs at various operating pressures. A discussion of the results of the test program follows.

Checkout Testing. This phase of the test program included calibrations, mechanical and electrical checks of the TSA and setting and maintenance of initial operating conditions. During checkout, it was observed that if product gases exited from the top of the module, there was a tendency for water vapor in the O_2 and H_2 to condense and "pool" in the O_2/N_2 and H_2/N_2 purge manifolds located at the bottom of the module. The build-up of the moisture made control of the moisture inside the module unstable. The test stand plumbing was rearranged so that the O_2 and H_2 product gases exited from the bottom of the module. This eliminated any moisture "pooling" from occurring inside the module. All the characterization and endurance testing was performed with the module plumbed in this configuration. In a zero gravity environment, "pooling" would not occur and the $O_2/N_2$and H_2/N_2 manifolds would be kept at operating temperature to prevent condensation.

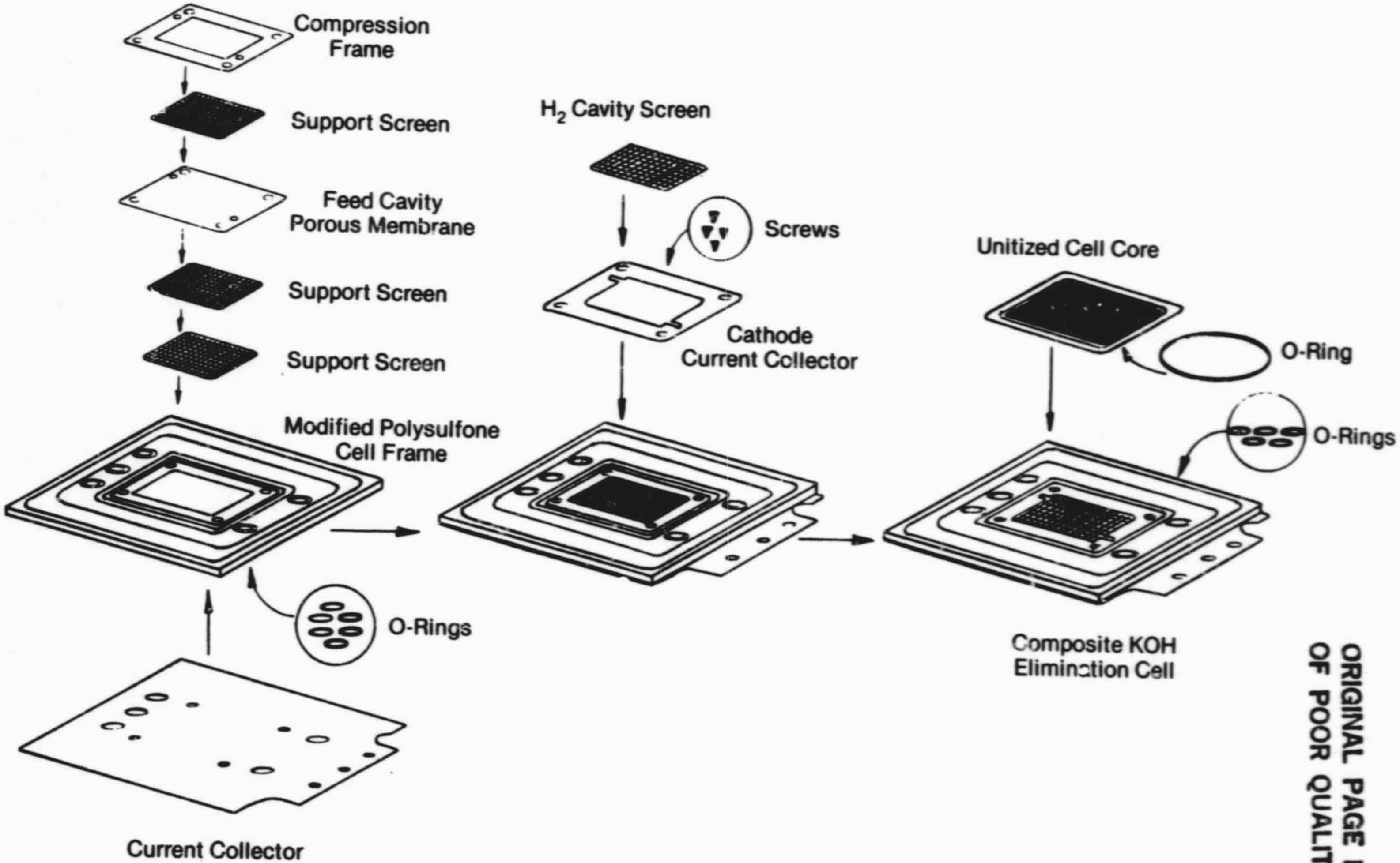

FIGURE 42 KOH ELIMINATION CELL ASSEMBLY CONCEPT

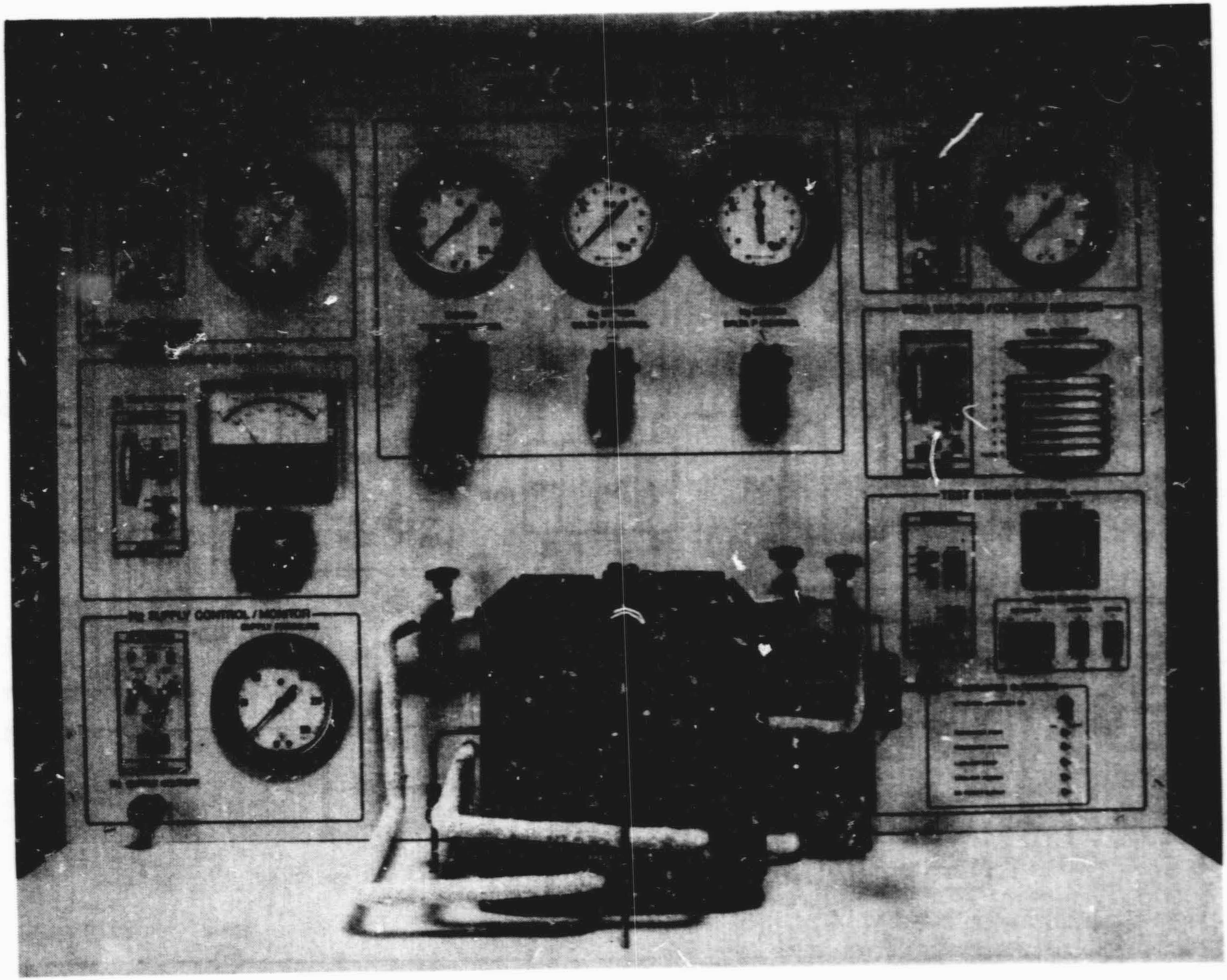

FIGURE 43 MULTI-PURPOSE HIGH PRESSURE TEST STAND

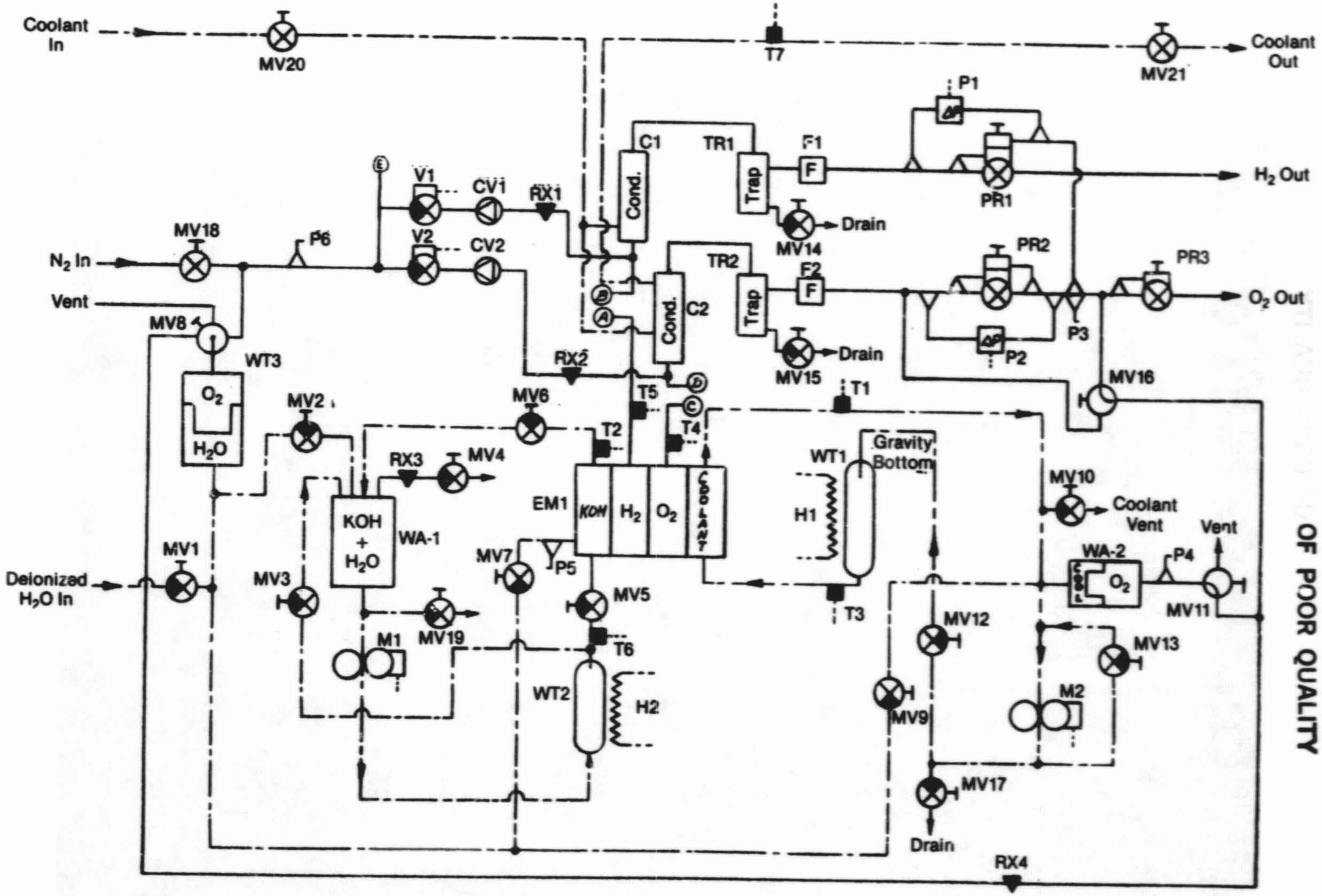

FIGURE 44 HIGH PRESSURE TEST STAND MECHANICAL SCHEMATIC

Characterization/Endurance Testing. During this phase of the test program, the KOH elimination module performance was observed over 675 hrs (approximately 28 days) of cumulative operation at variable conditions. One shutdown, due to a building power failure, occurred 216 hrs into the test. The results of this testing are shown in Figure 45. Initially, stable operating performance was obtained at 103 kPa (15 psia), 355 K (180 F) and 161 mA/cm^2 (150 ASF). During this operation, the temperatures of both the water feed circulation loop and coolant circulation loop were the same. This simulated a three-compartment cell design, since the coolant acted as the feed water circulation loop of an adjacent cell. After 270 hrs of operation at these conditions, the system operating pressure was increased to 345 kPa (50 psia). Operation at this pressure continued for approximately 100 hrs. During this time, an increase in the average cell voltage (from 1.60 V to 1.64 V) was noted.

The pressure was then increased to 517 kPa (75 psia). Initially, no increase in the average cell voltage was noted; after 140 hrs of operation at 517 kPa (75 psia), however, the average cell voltage had risen to 1.67 V. System pressure was increased to 794 kPa (115 psia) and then to 1,240 kPa (180 psia), Life Systems' baseline operating pressure. The module accumulated over 100 hrs of testing at 1,240 kPa (180 psia), 355 K (180 F) and 161 mA/cm^2 (150 ASF). The average cell voltage at these operating conditions remained steady at 1.69 V.

Continuous monitoring of cathode and anode electrolyte concentrations indicated that the KOH elimination module would sustain either a higher current density or a lower operating temperature. Both of these conditions would result in less water (i.e., higher KOH concentration) at both electrodes. Therefore, it is projected that the baseline operating conditions for a KOH elimination module would be 1,240 kPa (180 psia), 339 K (150 F) and 204 mA/cm^2 (190 ASF). Table 17 summarizes both the demonstrated operating conditions of this test program and the projected baseline operating conditions for future KOH elimination module testing.

Conclusions and Recommendations. It is concluded that stable operation of the KOH elimination module at the projected baseline operating conditions is possible. While the system operating pressure did not appear to have a great effect on the electrode electrolyte concentrations, it did have an slight effect on the cell voltage.

All 28 days of testing were performed at the same temperature and current density. During this time, the pressure was raised from ambient to 1,240 kPa (180 psia), yet the anode and cathode electrolyte concentrations remained between 12% and 18% KOH (except for a short period of time at the 360 hr mark of the testing). This implies that the cells' use of water is not strongly pressure-dependent and indicates the overall stability of the KOH elimination cell concept. This is projected to have benefits from a systems operation and control point of view. Temperature and current density conditions can be fixed and pressure can be independently increased or decreased.

The water must be kept at a pressure higher than the H_2 pressure. To accomplish this in an OGS, modification to the 3-FPC (which provides the reference pressure for the water tank) may be required. Further endurance testing at the projected baseline operating conditions is recommended to further determine water transport characteristics of the KOH elimination cell. This testing should be done utilizing a new cell design which is closer to the end application design.

Water Electrolysis Subsystem Alternate Purge Technique

Projected near-earth orbits for the Space Station exhibit 54 minutes of operation in the "light" side and 36 minutes in the "dark" side of the orbit. During the dark side of the orbit, the Space Station is constrained by limited power. To simulate these near-earth orbit conditions and minimize the use of "expensive" power, the WS-1 subsystem provides the capability for cyclic operation. The cyclic operation is characterized by a 54-minute period in "normal" operation followed by a 36-minute period in "standby" operation.

During the 36-minute standby portion of the WS-1 operating cycle, no current is applied to the module. No product gases are generated and, as a result, the module system pressure and differential pressures can decay through losses across regulator seats and, to a lesser degree, due to recombination of the H_2 and O_2 gases by diffusion through the cell matrices. Due to the difference between the O_2 and H_2 volumes in SFWE subsystems ($O_2 > H_2$), the pressure on the H_2 side decays much faster than the pressure on the O_2 side. This leads to a pressure imbalance within the SFWEM and can result in flooding-out of the H_2 compartment. In order to make up for these losses and maintain module operating pressures, N_2 has been used as a purge gas during the standby mode of operation. Aboard a spacecraft, this N_2 would come either from the N_2 source generating N_2 gas for cabin atmosphere or from a separate, expendable N_2 supply source. To eliminate the need for N_2 as an expendable for the OGS, an alternate source of maintaining module system pressure is needed. The following sections discuss a technique defined under this program which can be used to eliminate the use of N_2 gas during the standby portion of the OGS cyclic operating mode.

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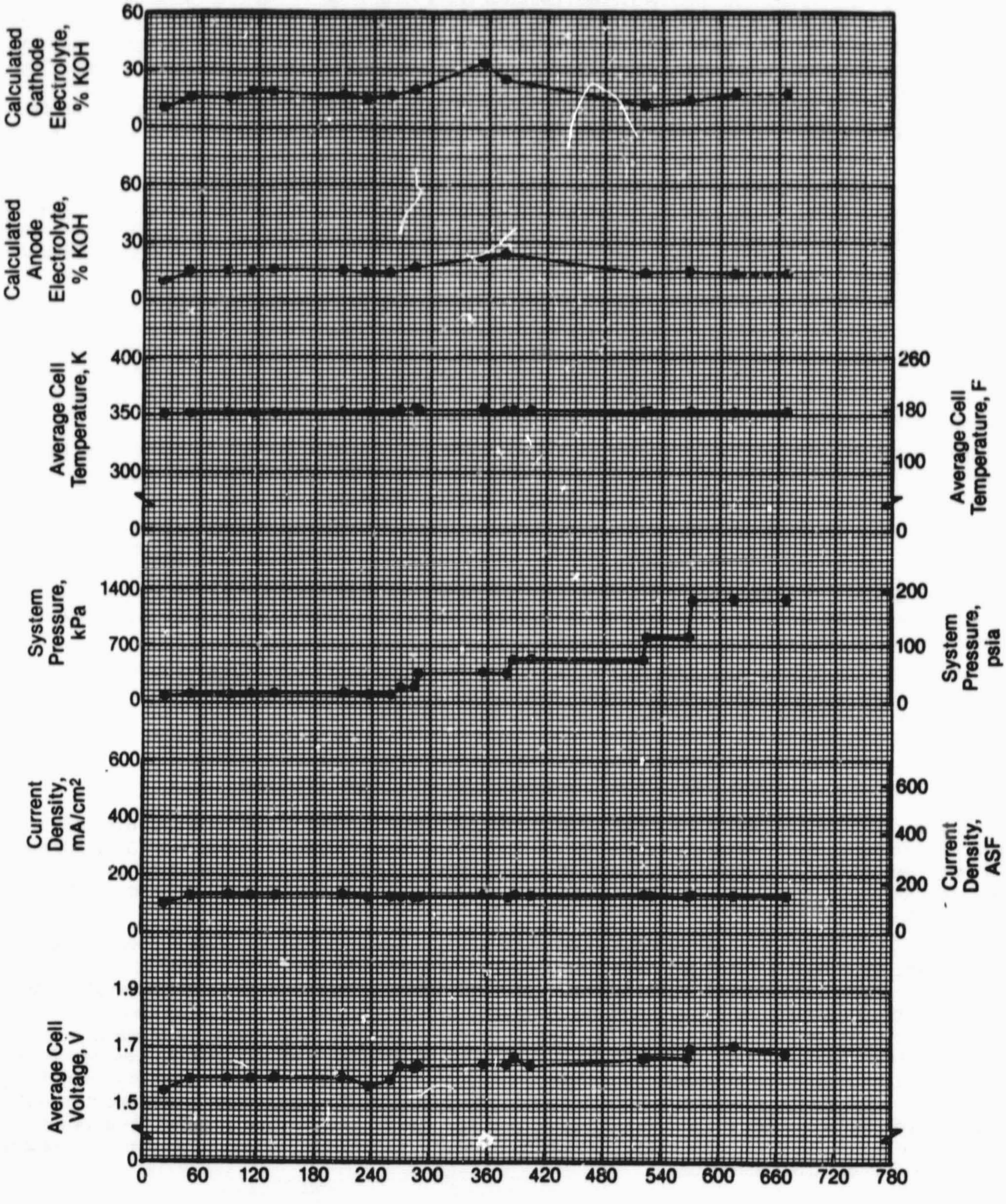

FIGURE 45 KOH ELIMINATION MODULE ENDURANCE TEST

TABLE 17 DEMONSTRATED AND PROJECTED BASELINE OPERATING CONDITIONS FOR KOH ELIMINATION MODULES

	Demonstrated Operating Conditions		Projected Baseline Operating Conditions	
Temperature, K (F)	355	(180)	339	(150)
Operating Pressure, kPa (psia)	1240	(180)	1240	(180)
H_2-to-System ΔP, kPa (psid)	13.8	(2.0)	13.8	(2.0)
H_2O-to-System ΔP, kPa (psid)	34.5	(5.0)	34.5	(5.0)
O_2-to-System ΔP, kPa (psid)	27.6	(4.0)	27.6	(4.0)
Current Density, mA/cm^2 (ASF)	161	(150)	204	(190)

Alternate Technique Analysis

Two techniques were examined which could be used to eliminate the need for N_2 gas during standby. Extra stored pressurized volumes of H_2 and O_2 gas could be used to create an overall large volume of O_2 and H_2 within an OGS. Whereas a small loss of gas from a small initial volume (subsystem without stored gas volumes) would be significant, the same small loss of gas from a much larger volume (system with stored gas volumes) would be insignificant. A "trickle," or low-level current, could also be used to generate just enough O_2 and H_2 to offset any losses and maintain system differential pressures during the standby mode. An evaluation of these two alternatives follows.

Extra Enclosed Storage Tanks. Using the ideal gas law, $PV = nRT$, the drop in gas pressure versus the gas loss rate over a 36-minute period for various total enclosed SFWEM volumes can be calculated. Using Faraday's Law and considering the total number of cells within the module, this gas loss rate can also be described in terms of an equivalent, proportional "recombination" current. This is equivalent to the trickle current that would need to be applied to offset recombination losses of the gases. (See next subsection.) Figure 46 illustrates the results of these calculations. The gas pressure will drop various amounts during the 36-minute standby mode depending on the O_2 loss rate and the total enclosed pressurized gas volume.

For an enclosed O_2 volume of 164 cm^3 (10 in^3), for example, a pressure loss of 13.8 kPa (2 psi) over a 36-minute period is equivalent to an O_2 loss rate of approximately 12×10^{-4} kg/d (2.7×10^{-3} lb/d). This rate corresponds to a recombination current of 27 mA. It can be assumed that for a constant O_2 enclosed volume the O_2 loss rate remains constant over the 36-minute period. Thus, the O_2 loss rate is the key parameter in determining the extra storage tank requirements.

For example, if it were desired to limit the O_2-side pressure decay to no more than 1.7 kPa (0.25 psi) and the O_2-side enclosed volume was 2048 cm^3 (125 in^3), no extra stored volume tank would be needed at an O_2 loss rate of 12×10^{-4} kg/d (2.7×10^{-3} lb/d) (see Figure 46). However, if the O_2-side volume was 164 cm^3 (10 in^3) an extra storage tank would be required for the same pressure drop limitations and O_2 loss rate. The volume of the extra tank required can be determined using Figures 47 and 48. From Figure 47, an O_2 loss rate of 12×10^{-4} kg/d (2.7×10^{-3} lb/d) is equivalent to an O_2 mass loss of 29.9×10^{-6} kg (6.5×10^{-5} lb). From Figure 48, an O_2 mass loss of 29.9×10^{-6} kg (6.5×10^{-5} lb) is equivalent to a pressurized volume of approximately 1311 cm^3 (80 in^3). Therefore, for an O_2-side volume of 164 cm^3 (10 in^3) an extra storage tank with a capacity of 1147 cm^3 (70 in^3) (total required volume of 1311 cm^3 (80 in^3) minus the existing volume of 164 cm^3 (10 in^3)) would be required to limit the O_2-side pressure drop to no more than 1.7 kPa (0.25 psi).

Based upon technical information concerning lightweight gas storage tanks, the estimated weight of extra enclosed pressurized volumes is approximately 6.4×10^{-4} kg/cm^3 (0.023 lbs/in^3). Thus, for a hypothetical total enclosed subsystem O_2 volume of 164 cm^3 (10 in^3), a stored volume tank on the O_2 side with a capacity of approximately 1147 cm^3 (70 in^3) would have an equivalent weight of approximately 0.73 kg (1.61 lbs).

With respect to H_2-side volume calculations, since twice as much H_2 would be consumed as O_2, the required extra pressurized stored volume tank on the H_2 side (for similar module conditions) would be approximately 2,458 cm^3 (150 in^3), or an additional 1.57 kg (3.45 lbs). The total minimum weight penalty for these two tanks would be 2.30 kg (5.06 lbs). As the O_2 loss rate (and corresponding recombination current) increased, the storage tank volume requirements would increase significantly.

Trickle Current. To evaluate an equivalent weight penalty for the use of trickle current, a manual, breadboard test was performed using an existing test facility and a 12-cell 0.1 ft^2 SFWEM. Manual shutoff valves were installed in the product gas lines downstream of the SFWEM to ensure enclosed, pressurized product gas volumes within the system and limit pressure decay to that resulting from O_2/H_2 recombination effects. Once system operating pressures were established, the current to the module was alternately turned off and then turned back on. The objective was to allow the module pressures to decay and then determine if they could be increased, maintained and controlled by intermittent application of a low-level current.

The trickle current demonstration data for this test is shown in Figure 49. At "Time = Zero" of Figure 49, the shutoff valves were manually closed and the module current was manually reduced to zero. The H_2-to-System differential pressure was used as the control parameter and was permitted to decay to 7 kPa (1 psid), at which time a current of 0.5 A was applied to the module. The H_2 differential pressure was then permitted to increase to 21 kPa (3 psid), at which time current was again manually reduced to zero. The data from Figure 49 illustrates that the ΔPs were controllable by pulsing the 0.5 amp current, for nominally, three minutes on/four minutes off. This is equivalent to a 43% duty cycle ("On" Time divided by ("On" Time + "Off" Time)). Figure 49 further illustrates that differential pressures could be maintained without decay with constant application of 0.25 amps.

For the 12-cell module operating at an average cell voltage of 1.44 V per cell, use of a 0.5 amp current pulsed at a 43% duty cycle rate required 3.7 watts to maintain module pressures (0.5 A x 1.44 V x 12 x 0.43). Based upon a power penalty of 0.268 kg/W (0.591 lb/W), an equivalent weight penalty for use of the trickle current with the 12-cell module would be 0.99 kg (2.19 lb).

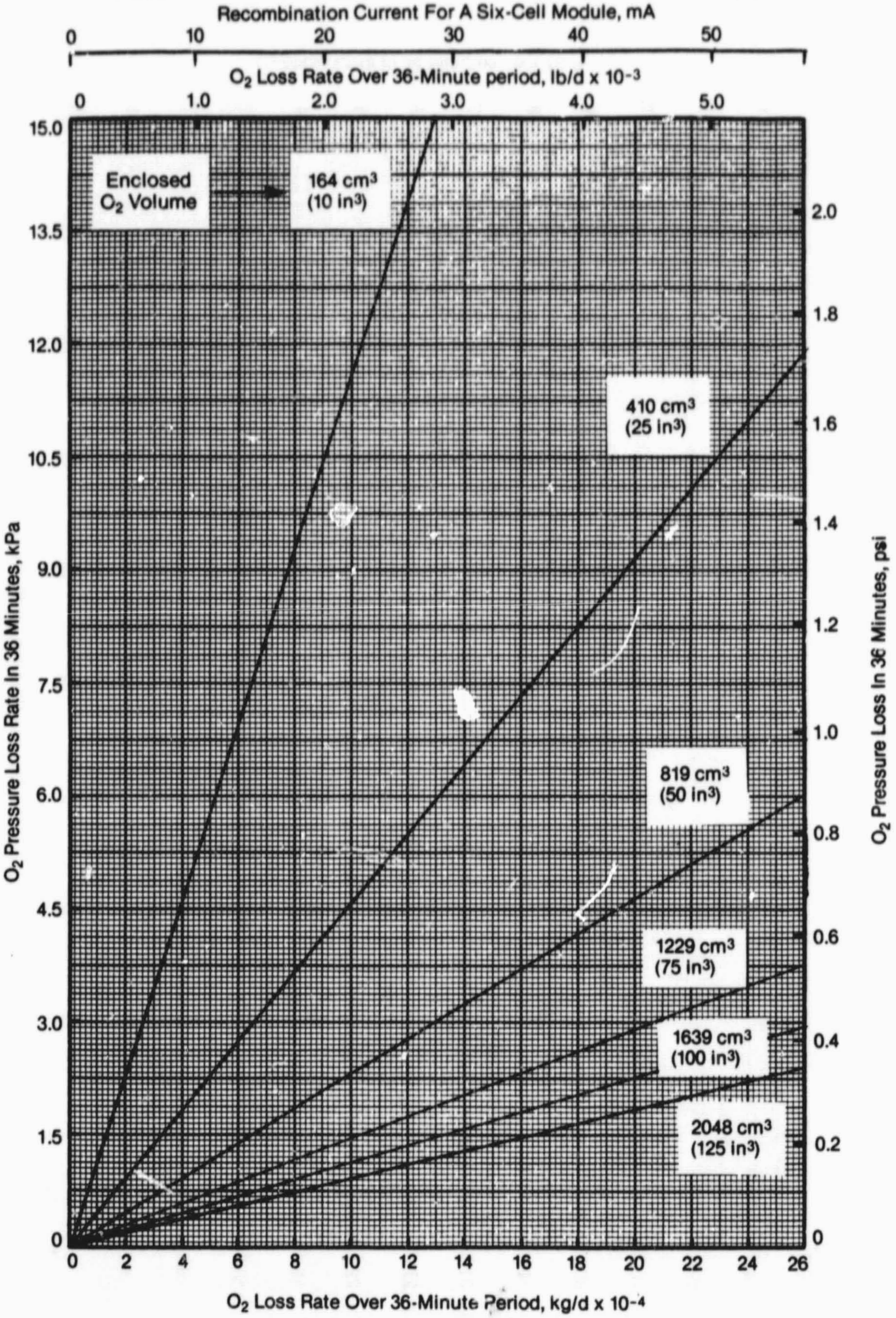

FIGURE 46 O_2 PRESSURE LOSS VERSUS O_2 LOSS RATE FOR VARIOUS ENCLOSED VOLUMES

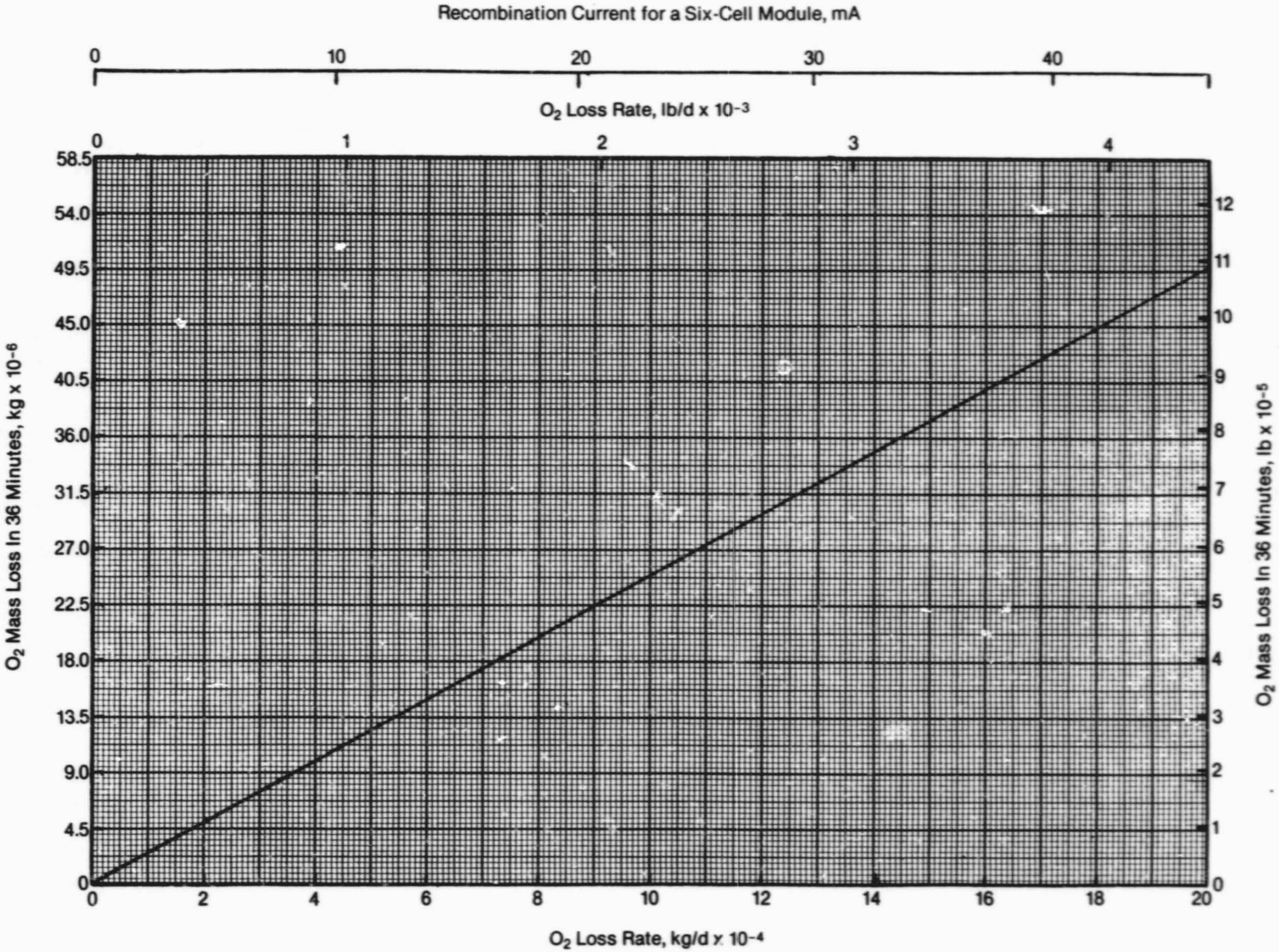

FIGURE 47 O_2 MASS LOSS IN 36 MINUTES VERSUS O_2 MASS LOSS RATE

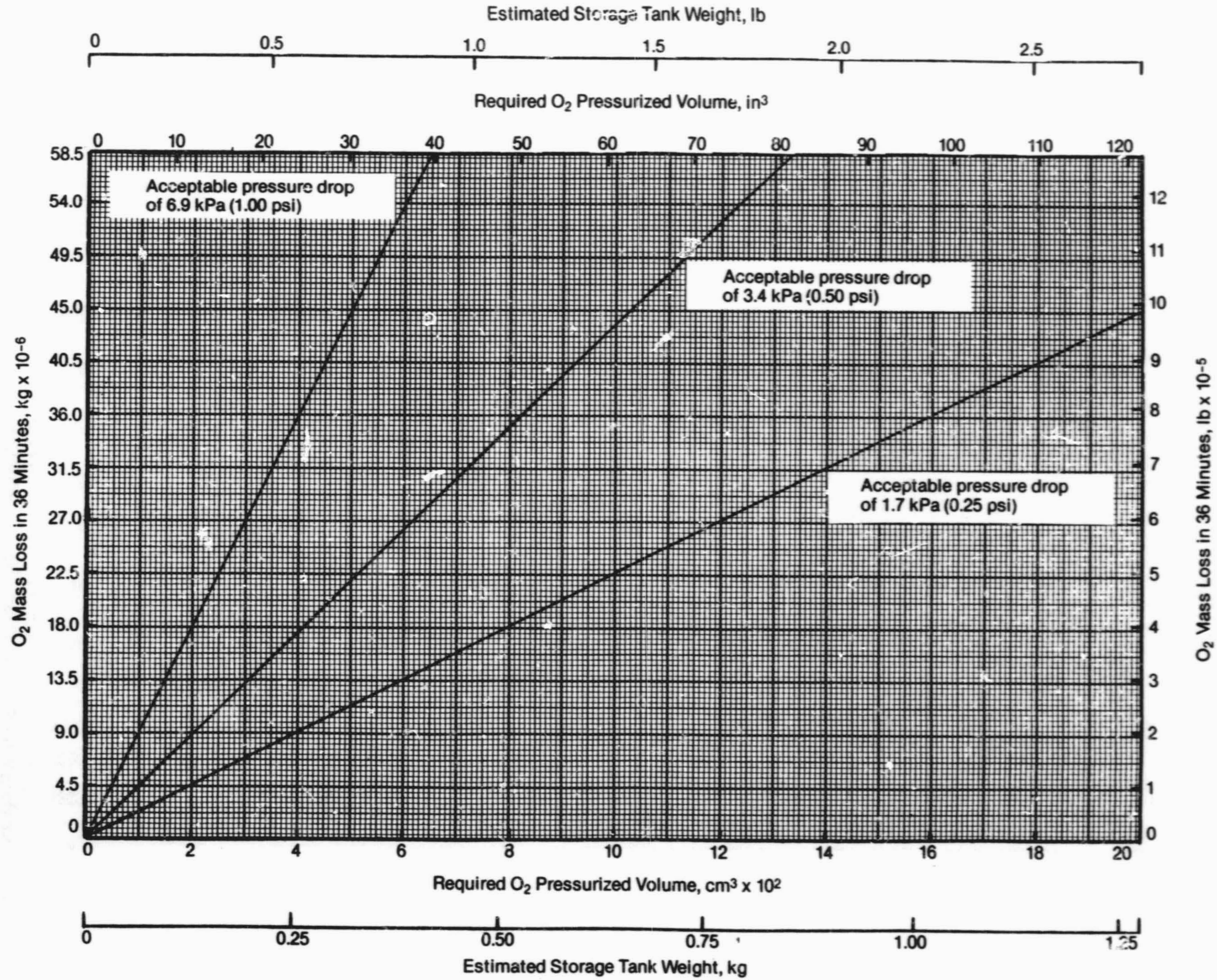

FIGURE 48 TOTAL O_2 MASS LOSS IN 36 MINUTES VERSUS REQUIRED O_2 PRESSURIZED VOLUME

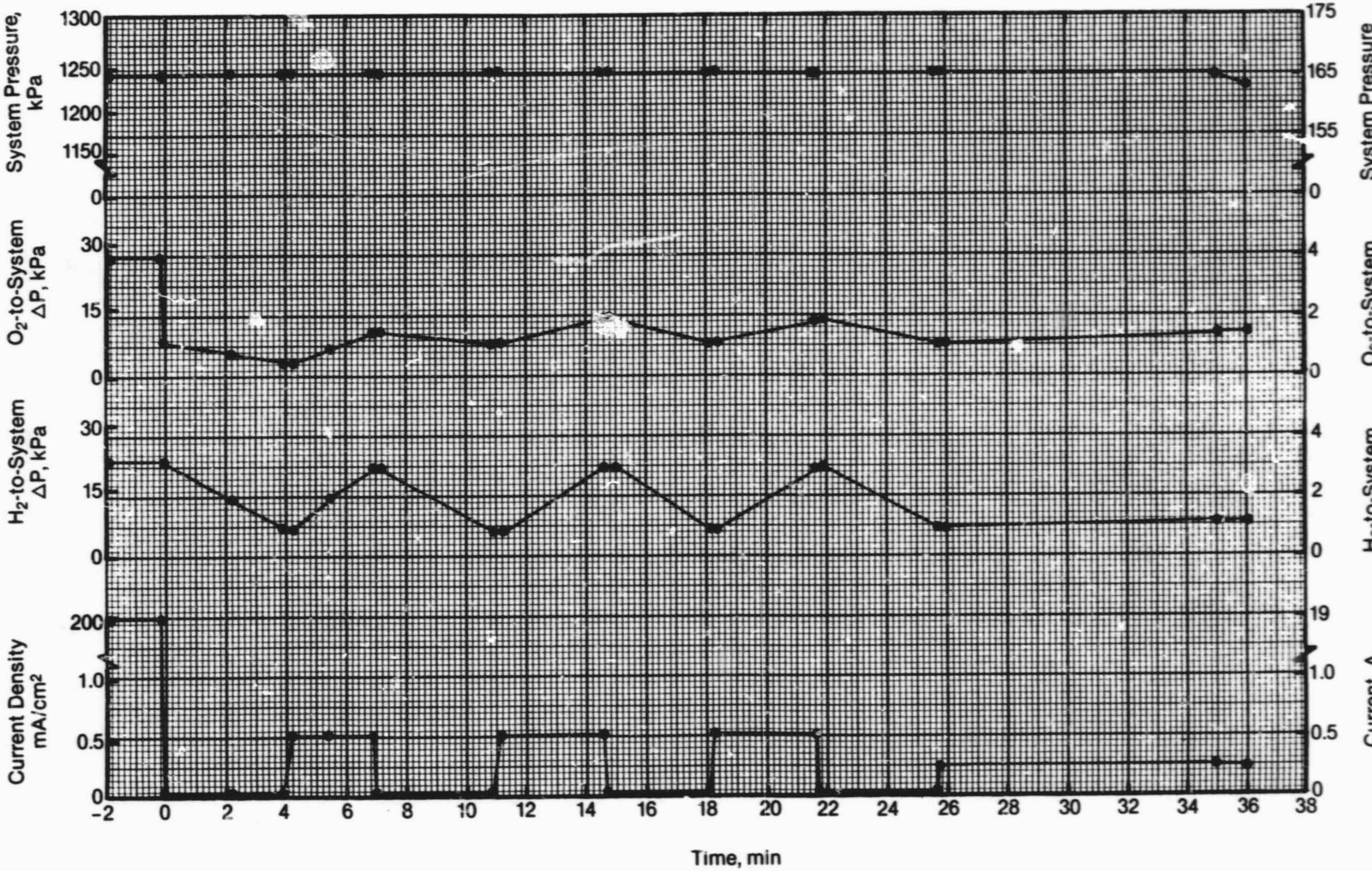

FIGURE 49 ALTERNATE PURGE TECHNIQUE: TRICKLE CURRENT DEMONSTRATION (12-CELL MODULE)

For this particular test set-up, the enclosed gas volumes up to the shutoff valves were calculated to be 144 cm^3 (8.8 in^3) in the H_2 line and 2,261 cm^3 (138 in^3) in the O_2 line. The theoretical total weight penalty for the use of storage tanks with this set-up would be 1.67 kg (3.68 lb).[a]

By contrast, the equivalent weight penalty to maintain a 27 mA trickle current equal to the corresponding hypothetical recombination current would be only 0.99 kg (2.19 lb).

Thus, hypothetically for the 12-cell module, the trickle current technique would represent a 40% weight savings over the stored volume. However, the actual current level required to maintain module operating pressures (nominally 250 mA continuous current) was significantly higher than the hypothetical recombination current of 27 mA. This indicated that actual required stored volumes would be significantly greater (and impart a greater weight penalty) than the hypothetical volumes. Using a recombination current of 250 mA and extrapolating the data from Figures 46 through 48, the actual required storage tank on the O_2 side would occupy approximately 12,600 cm^3 (769 in^3) and weigh 8.06 kg (17.73 lbs). Since the storage tank on the H_2 side would be twice as large as that on the O_2 side, the total calculated weight penalty for the extra storage tanks would be 24.18 kg (53.19 lb). It is clear, therefore, that the trickle current has a distinct weight advantage. Since a trickle current would involve only small volume electronics, the trickle current concept also has a volume advantage.

WS-1 Subsystem Demonstration

A semi-automatic demonstration of the trickle current technique was performed using the WS-1 subsystem. Based upon the 12-cell module trickle current demonstration data, a 6-cell module operating at the same conditions (average voltage, duty cycle rate, etc.) was projected to require 1.85 W (an equivalent weight penalty of 0.50 kg (1.09 lb) to maintain module pressures.

A breadboard trickle current controller circuit was fabricated and wired into the WS-1 C/M I. The Subsystem software was modified to provide control over the trickle current controller circuit. Normally-open solenoid valves were installed in the H_2 and O_2 product gas lines downstream of the 3-FPC. When the WS-1 subsystem was manually switched from Normal operation to Standby operation, the trickle current control circuit was enabled. The control circuit would then immediately close the product gas line solenoid valves and control current to the module using the existing C/M I power supply. The H_2 differential pressure was used as the power supply control parameter. When the H_2 differential pressure fell below 16 kPa (2.3 psid), the trickle current controller circuit would initiate application of current to the module; when the H_2 differential pressure rose above 19 kPa (2.7 psid), the controller circuit would shutoff current to the module. The C/M I power supply was able to provide a minimum controllable current of 0.75 A. This was not considered detrimental to the objectives of the test, however, since it was anticipated that the application of a somewhat higher trickle current would be offset by a reduced duty cycle rate.

The results of the WS-1 subsystem trickle current demonstration are shown in Figure 50. Upon switching to the Standby mode of operation and enabling the trickle current controller and software routine, the H_2 differential pressure fell rapidly to zero. The differential pressure was not quickly recoverable using the lowest current available, so the current was increased and maintained until the H_2 differential pressure was recovered. After this point, the H_2 differential pressure was easily controlled and maintained at lower current levels. The O_2 differential pressure decayed steadily to zero since when the O_2 product gas line solenoid valve was closed, the O_2 pressure within the closed line equilibrated and eliminated a "differential" pressure across the pressure transducer within the line.

As can be seen in Figure 50, the H_2 differential pressure was easily controlled between its upper and lower setpoints using a 0.75 amp current pulsed for, nominally, 11 seconds on and 27 seconds off. This represented a 29% "On" Time duty cycle. The WS-1 WEM operated at an average cell voltage of 1.40 V per cell. This yielded a power requirement of 1.83 watts to maintain module pressures, virtually identical to the projections based on the 12-cell module data.

Conclusions and Recommendations

The trickle current demonstrations verified the concept and advantages of the use of a trickle current over the use of extra stored volumes to maintain subsystem pressures during the Standby mode of operation. Based on the test results, it is projected that N_2 gas can be eliminated as a pressurization source during the Standby mode of operation. It is recommended that additional testing be performed with the WS-1 Subsystem to evaluate the initial loss of H_2 differential pressure experienced immediately after switching to the Standby mode and to quantify the minimum trickle current capable of maintaining subsystem pressures. Also, to eliminate the need for the additional solenoid shutoff valves in the product gas lines, the 3-FPC design should be upgraded to provide for positive shutoff capability.

(a) Using the hypothetical recombination current and pressure loss limitations discussed in the text (27 mA and 1.7 kPa (0.25 psi), respectively), extrapolation of the information presented in Figures 46 through 48 results in a theoretical H_2-side extra enclosed storage tank volume of greater than 2,622 cm^2 (160 in^3). The weight penalty for this tank would be not less than 1.67 kg (3.68 lb). Due to the large enclosed volume on the O_2 side, no enclosed storage tank would be required (at a theoretical recombination current of 27 mA).

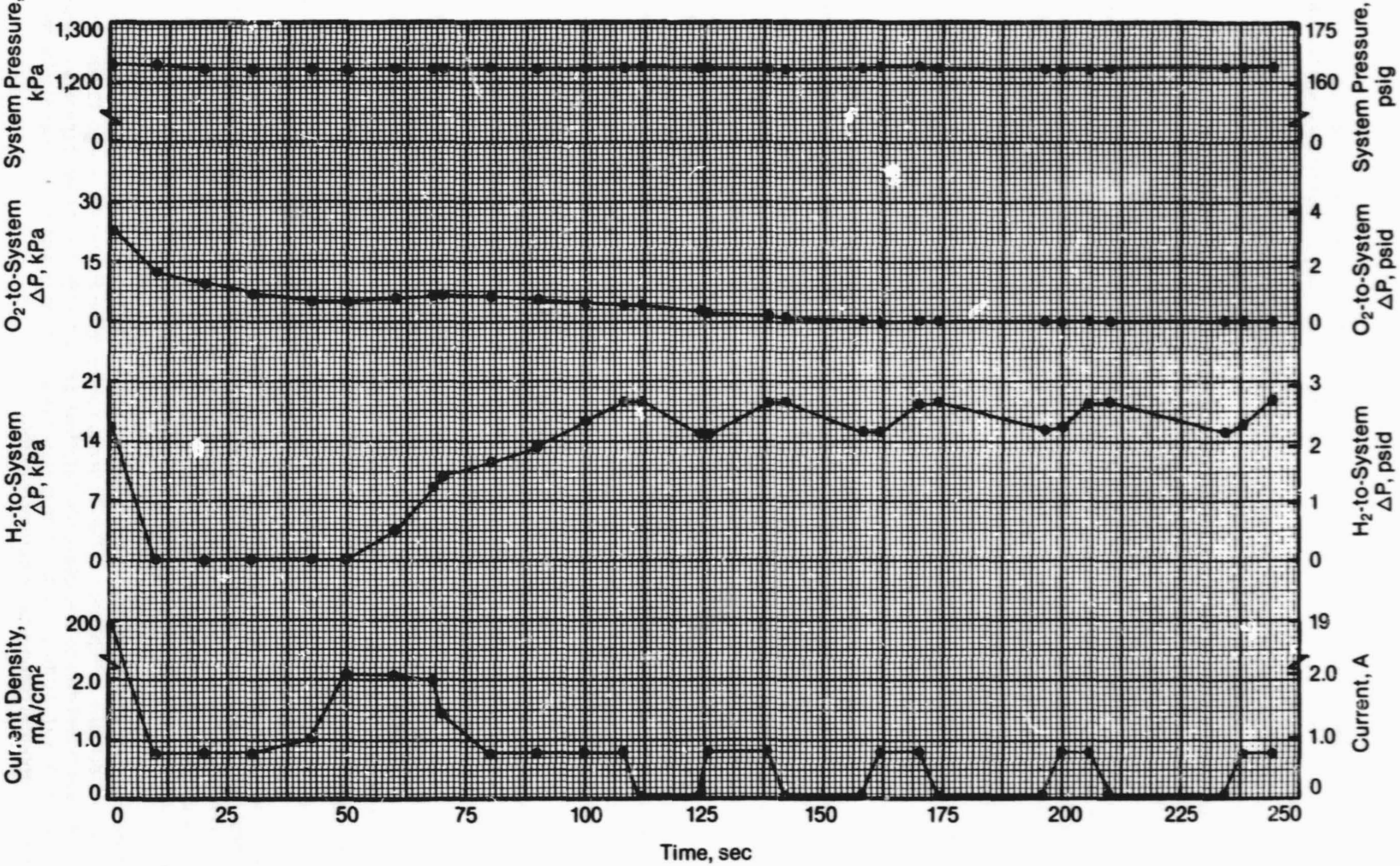

FIGURE 50 WS-1 SUBSYSTEM TRICKLE CURRENT PURGE TECHNIQUE DEMONSTRATION

PRODUCT ASSURANCE

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractural performance, including design, purchasing, fabrication and testing. The product assurance program included Quality Assurance, Reliability, Maintainability and Safety functions. Quality Assurance was necessary to ensure reproducibility of designs and configurations during subsequent developments. Reliability was included to ensure that test equipment and test data gathering and recording were basic factors in the development of component and subsystem reliability and long life. Maintainability was included to identify parameters for routine and nonroutine maintenance requirements. Safety was included to ensure that no system or system component characteristic would be dangerous to personnel or equipment during testing.

Quality Assurance

The activities performed during this effort were included to ensure that no defective components or parts were incorporated into the test hardware. These activities consisted of performing receiving inspection of all vendor supplied parts, including preparation of required documentation; ensuring that assembly techniques specified in design drawings were complied with and were consistent with the developmental nature and scope of the program; and ensuring that configuration control was provided by monitoring the drawing and change control procedures. Quality assurance was active in monitoring all test activities.

Reliability

Reliability personnel participated in the program to ensure (1) proper calibration of test equipment and TSA instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations. Calibration and test requirements for each subsystem and component were determined. Appropriate components were calibrated during assembly and after installation. A test procedure was established to ensure that all parameters would be properly monitored and that the testing would conform to the program's Quality Assurance and Safety procedures. All major testing required that a test plan be completed and reviewed.

Maintainability

A Maintainability function was carried out during the design and testing phases of the program. During design phases, the emphasis was placed on configuring the hardware and test stand components for accessibility with respect to maintenance activities. During the testing phases, logs of scheduled and unscheduled maintenance were maintained. Logs were prepared which detailed operational problems and their sources, the corrective actions taken and the operations and time required to implement the corrective actions.

During the design phases, Shutdown Avoidance Analyses were performed. The objective was to identify preventive shutdown measures to increase the amount of test data obtained per test dollar and ensure that a shutdown caused by an out-of-tolerance condition would not damage components. The results of the analysis included the following:

1. All hardware and software were checked out and debugged prior to installation into the subsystem or TSA.
2. All parameter level setpoints were checked out to ensure that the level warning lights operated by simulating inputs at the sensors and verifying these inputs.
3. All sensors were calibrated as required.
4. Where applicable, operational transitions were automated in order to avoid human error caused by manual operation.

During the testing phase of the program, Life Systems' Failure Reporting Procedure was implemented. This procedure establishes the requirements for reporting, investigating and correcting a product operational failure. The purpose of the procedure is to enable Life Systems to monitor those product problems which relate to component or subsystem operation or design, together with the corrective action taken against each problem, and to assist in assuring that the final corrective action achieves maximum effectiveness.

Safety

A safety program was initiated to assure adherence to safety standards andprocedures essential to protect personnel and equipment. The program consisted of identifying possible adverse component or subsystem characteristics, reviewing

designs and design changes for potential safety hazards, reviewing NASA Alerts for safety information and incorporating the equipment's protective features. The safety program included the following activities:

1. Although metallic and nonmetallic material control was not required contractually, all materials were subjected to informal evaluation during design and manufacturing phases. Nonmetallics were evaluated for their compatibility with atmospheres and corrosive media to which the nonmetallic might be exposed. Metallic materials were evaluated with regard to corrosion resistance and strength criteria.
2. Human Engineering considerations were given to both operation and maintenance. All known possibilities of human error were eliminated, with primary emphasis being given to possible accidental activation of components or subsystems. Where feasible, fluid line end fittings or connections were used with dimensions or configurations which would not permit incorrect installation of a fluid line.
3. Electrical design considerations included prevention of electrical equipment shock hazard, protection against inadvertent actuation of switches, use of current limiting devices on electrical equipment which could contact personnel or other conductive equipment, use of warning labels on all access panels leading to high voltages, and design of wire bundles to have the ability to withstand anticipated handling and operating deformations without wire damage.
4. Sharp edges and corners were eliminated or were adequately covered with a protective cushion in order to prevent injuries.
5. Items exhibiting elevated surface temperatures and which might be leaned on, brushed against or held up to 10 seconds were insulated so that surface temperatures would not fall outside the range of 60-120 F.

CONCLUSIONS

Based upon the work completed, the following conclusions are drawn:

1. After 124 days of operation, the WS-1 OGS continued to meet the O_2 metabolic requirements for one-person, as designed. Previously demonstrated state-of-the-art single cell performance was virtually duplicated at the module level. Subsystem and hardware reliability were demonstrated over 2,980 hours of cumulative operation.
2. The 3-FPC has demonstrated its capability as an effective, reliable integrated pressure controller. After 8,650 hours of cumulative operation, the 3-FPC verified its ability to control SFWES gas pressures.
3. Based upon the results of a 30-day cyclic test, the WES FCA has been shown to be a reliable technique for WES fluid handling requirements. The hardware can effectively reduce subsystem complexity and increase SFWES operational reliability.
4. The unitized core concept demonstrated excellent operational capabilities at both the single-cell and module levels. Single-cell endurance testing for 720 hours demonstrated the capability of the unitized core to operate at differential pressures up to 83 kPa (12 psid). A 720-hour endurance test at the six-cell module level verified the performance and reliability of the unitized core. Based upon the results of the testing, overall water electrolysis cell complexity can be reduced and cell operational capabilities and reliability can be improved by use of the unitized core concept.
5. The viability of the feedwater electrolyte elimination concept was demonstrated over 675 hours of testing at the module level. The results of the testing indicated that the KOH elimination technique had operational capability across a wide range of operating pressures. The data provided further justification for continued cell design improvement and testing.
6. An alternate technique for eliminating the use of nitrogen purge gas and still maintaining OGS subsystem operating pressures during the Standby mode of operation was successfully demonstrated, using both a 12-cell SFWEM and the six-cell WS-1 Subsystem. Use of a trickle current was shown to have at least a 40% weight savings advantage over the supplementary storage tank concept for OGS Standby operation purge/pressurization. The trickle current concept is considered to be a valid and promising technique for OGS operation during the 36-minute limited-power portion of a near-earth orbit.

RECOMMENDATIONS

Based on the work completed the following recommendations are made.

1. Perform analyses, studies and developments to advance the development level of static feed water electrolysis-related hardware components, including instrumentation, with a goal of improving overall performance and Space

Station applicability of the subsystem. This would include design and fabrication of an injection mold for the baseline unitized core/composite cell static feed water electrolysis design, the goal being to eliminate manual assembly steps, use the feed compartment water as the coolant, reduce bulk and incorporate internal manifolding to avoid back-to-front external fittings and plumbing.

2. Evaluate subsystem weight savings and volume impact by the use of lightweight end plates consisting of either a honeycomb or composite material.
3. Establish and incorporate fail-safe operation into the existing static feed water electrolysis baseline design, utilizing the Built-In Diagnostic (BID) concept, availability of a primary and secondary power source, and emergency controller functions.
4. Generate reliability data from which spares and maintainability approaches can be determined by a standard endurance testing of the WES FCA in its test stand, additional extended endurance testing of the 3-FPC in its test stand, extended endurance testing of the unitized core/composite cell six-cell module and extended endurance testing of the WS-1 subsystem.
5. Perform an extended endurance test on the KOH elimination module, and characterize it for start, stop and standby operating modes and temperature ranges over which it can operate successfully.
6. Eliminate the separate coolant compartment from the baseline static feed water electrolysis module. This will allow for conversion of the present four compartment cell to a three compartment cell and will reduce weight, volume and subsystem complexity. Fabricate and test a SFWEM incorporating the feed compartment KOH elimination and coolant compartment elimination technologies.
7. Perform studies, analyses and designs necessary to incorporate the static feed water electrolysis O_2 generation function into an integrated air revitalization system. This activity would focus on ground and potential flight verification testing.

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